AN EXPERIMENTAL STUDY FOR THE PREDICTION OF PRESSURE LAG INHERENT IN BALLISTIC MISSILE PLUMBING SYSTEMS--PART II

A THESIS

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AN EXPERIMENTAL STUDY FOR THE PREDICTION
OF PRESSURE LAG INHERENT IN BALLISTIC
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Sept 6, 1958

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D	inside diameter of test line, inches
K	time constant, 1/seconds
L	length of test line, inches
ΔP	pressure lag, $P_R - P_I$, mm of mercury
P_I	input pressure, mm of mercury
P_R	response pressure, mm of mercury
t	time, seconds

SUMMARY

This report presents the results of an experimental study for the prediction of pressure lag in typical systems of tubing used in ballistic missiles for measuring ambient pressures. Representative rates of change of input pressures for ballistic missile ascent trajectories were obtained by means of an orifice plate. The test system consisted of tubing of variable length and inside diameter, and with a 1.7 cubic inch volume at the downstream end. Pressure inputs at the upstream end of the test system were sensed by absolute pressure transducers, while the difference in pressure between the upstream and downstream ends of the test system was measured by a differential pressure transducer. The electrical outputs from these transducers were amplified and recorded by brush-type recorders. Experiments were conducted with four missile ascent trajectories and with the following test geometries: (1) line lengths of 30, 45, 60, and 75 inches and (2) line inside diameters of 0.0625, 0.125, and 0.15625 inches.

From the experimental data obtained in this investigation, the following conclusions were reached:

1. The magnitude of the pressure lag is affected more by changing the line inside diameter than by changing the line length.

2. A small increase in pressure lag occurs when changing from a 0.15625 inches to 0.125 inches inside diameter test line for all trajectories and constant lengths. However, a large increase in pressure lag occurs when changing from a 0.125 inches to a 0.0625 inches inside diameter test line.

3. The variation of pressure lag with length is approximately linear for constant line inside diameter.

4. In general, the pressure lag was increased by decreasing line inside diameter, by increasing line length, and by increasing the rate of change of pressure for a given missile trajectory.

5. In missile pressure sensing systems, the use of tubing with inside diameter below 0.125 inches would yield unreliable data due to the large pressure lag.

CHAPTER I

INTRODUCTION

The pressure measured over a ballistic missile trajectory varies considerably in both the level of pressure and the rate of change of pressure. Due to weight and space limitations of the missile, it is not always feasible to use optimum tubing dimensions to eliminate the pressure lag in the pressure measuring system. It is necessary to know the effects of the system variables on the pressure lag in order to correct the measured pressures and thus aid research of the upper atmosphere.

The purpose of this experimental study is to determine the effects of line inside diameter, line length, and the trajectory or rate of change of ambient pressure on the pressure lag of the measuring system. Experimental information is presented to show the relationship between pressure lag, inside diameter, and length of the test line with trajectory as a parameter. Although the trajectories investigated are similar to trajectories for multi-stage missiles, it is possible to establish a maximum limit for the pressure lag which would be encountered during the flight of a single-stage missile. The pressure lag data obtained from the investigation of a multi-stage missile will usually overestimate the pressure lag data obtained from a single-stage missile.

CHAPTER II

APPARATUS

Figure 1 shows the major components of the apparatus which were used in the investigation: the vacuum pump and tank section, the gauge section, the diaphragm section, the system of plumbing to be tested, and the necessary instrumentation for calibrating and recording the pressures. In order to make the system flexible with regard to leak checking and transducer calibration, valves were installed isolating each section. A brief description of each section of apparatus follows.

Vacuum Pump and Tank Section.--Three high-vacuum pumps were used to evacuate the storage tanks. These storage tanks, two 8,000 cubic inches and one 2,000 cubic inches, provided the vacuum source. A fourth high-vacuum pump was installed for use in calibrating the transducers. Two filters were located between the pumps and the tanks to remove any foreign matter which might have damaged the pumps. All connecting lines were one-half inch copper tubing with soldered sweat-type joints.

Gauge Section.--Four vacuum gauges were located on the upstream side of the diaphragm section and were used either for calibration of the transducers or as indicators of the pressure level in the storage tanks before and after a test run. The ranges of the gauges were: (1) 400-800 mm of Hg; (2) 0-400 mm of Hg; (3) 0-100 mm of Hg and (4) 0-20 mm of Hg. All gauges were accurate to 0.1 per cent of their full scale range.

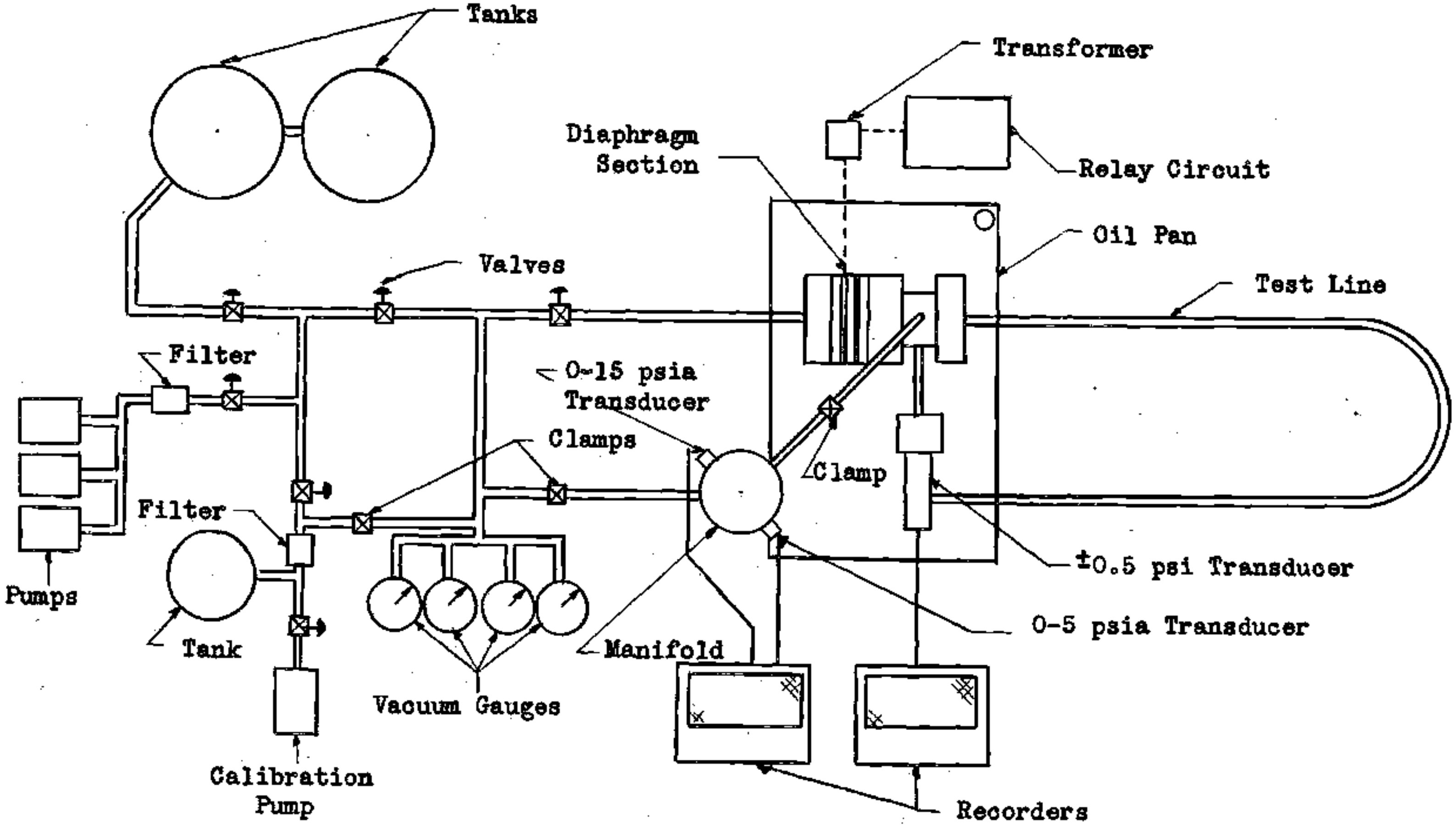


Fig. 1 Schematic Diagram of Test Apparatus

<u>Diaphragm Section</u>.--The diaphragm section is shown schematically in Fig. 2. Rubber gaskets and "O" rings were used to obtain a tight seal. Mylar Polyester Film, 0.5 mil thick, was used for the diaphragm material. Four platinum wire elements, each 0.010 inches in diameter and fastened to two copper leads 0.125 inches wide and 0.005 inches thick, were sandwiched between two layers of the plastic diaphragm material in positions to cover the holes in the orifice plate. Because of a leak problem in extending the copper leads out of the diaphragm section, it was necessary to submerge the complete diaphragm section in an oil bath. A voltage of 21 volts from a transformer in conjunction with a resistance-capacitance relay circuit was used to heat the platinum wire incandescently and to rupture the diaphragm in front of each hole in the orifice plate. The time of rupture for the diaphragm was controlled by the relay circuit. Variation of hole size in the orifice plate and change in time of rupture of the diaphragm across each hole yielded the four different trajectories presented in this investigation.

<u>System of Plumbing to be Tested</u>.--The system to be tested was mounted, with its associated plumbing, on a heavy wooden table. This system consisted of the test line and a 1.7 cubic inch end volume. The test lines were seamless, steel tubing in lengths of 30, 45, 60, and 75 inches with the line inside diameters of 0.0625, 0.125, and 0.15625 inches, respectively. A rubber-tube coupling connected the test line to the diaphragm section (Fig. 2). In order to measure the differential pressure across the test line, each tube was bent in the form of a "U" with approximately a 3.5-inch radius bend. Table 1 gives a summary of the variables to be tested.

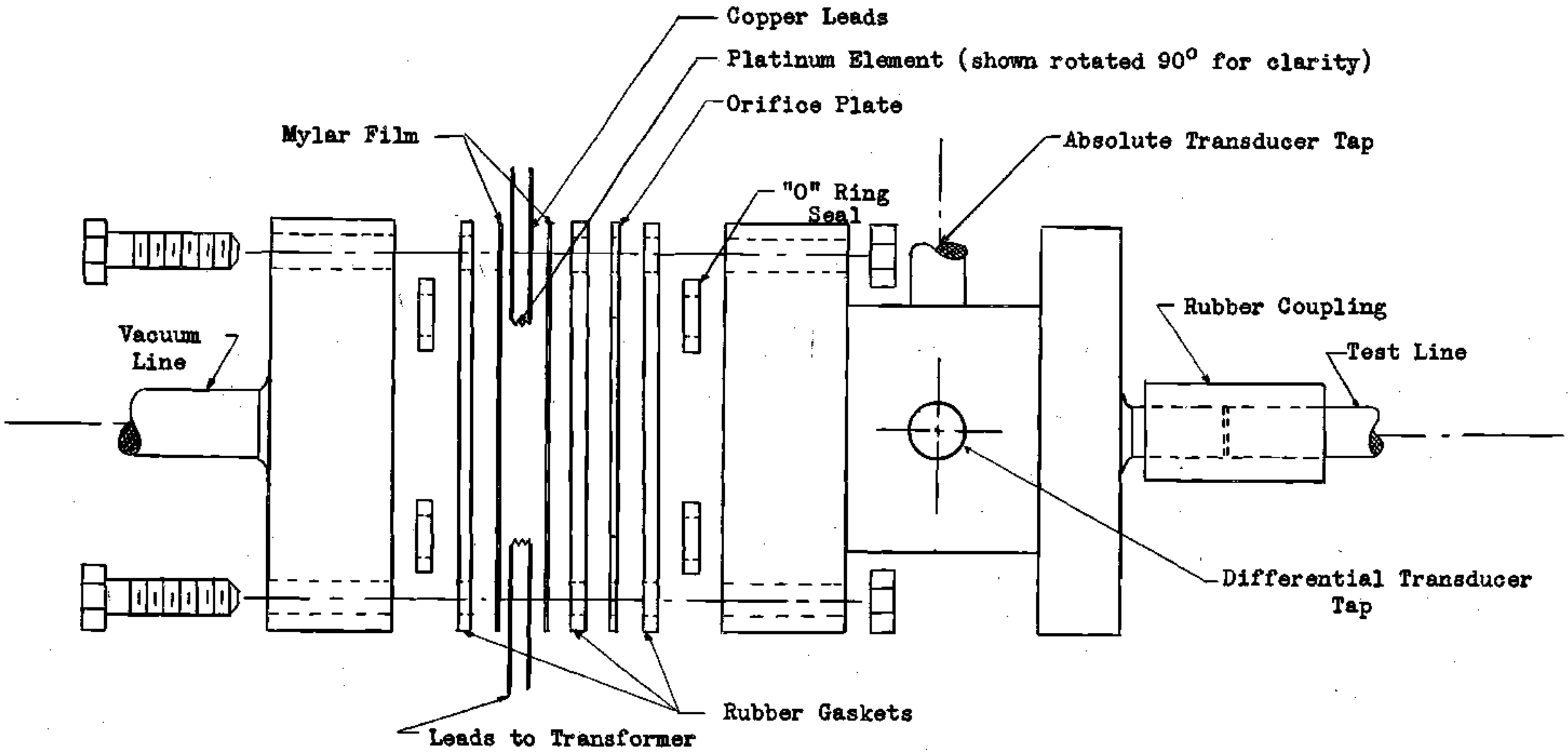


Fig. 2 Schematic Diagram of Diaphragm Section

Table 1. Variables Tested

Variable	Dimension	Specification
Trajectory	--	#1 #2 #3 #4
Line Length	inches	30 45 60 75
Line Inside Diameter	inches	0.0625 0.125 0.15625

Instrumentation.--In order to measure the absolute transient pressures, two absolute pressure transducers were housed in a manifold and connected directly downstream from the diaphragm section by short, flexible, rubber tubing (Fig. 2). The transducers were temperature compensated and had full-scale ranges of 0-15 psia and 0-5 psia, respectively. The pressure lag or instantaneous pressure differential across the test line was measured by a differential transducer with a range of ±0.5 psi.

Outputs from both types of transducers, absolute and differential, were amplified and recorded by two brush-type recorders. These recorders gave an immediate readout through a pen tracing the pressure characteristics on a moving chart.

A more detailed description of the test apparatus is given in reference 1.

CHAPTER III

PROCEDURE

The experimental work was conducted at the Daniel Guggenheim School of Aeronautics of the Georgia Institute of Technology.

The following test procedure was used for all the variables investigated.

Calibration.--Each of the absolute pressure transducers was calibrated daily before any tests were begun. The 0-15 psia transducer was calibrated over a range of 0-745 mm of Hg spread over 10 inches of paper. To obtain more accuracy at low pressures, the 0-5 psia transducer was calibrated over a range of 0-24 mm of Hg with a 10-inch spread on the recorder paper. For all calibrations of the absolute transducers the vacuum gauges were used as standards. Each daily calibration was compared with calibrations of previous days.

The differential transducer was calibrated approximately every third day over a range of 10 mm of Hg, again spread over 10 inches of paper. A micromanometer was used as the calibration standard for this transducer. From preliminary data it was found that 10 mm of Hg would be the maximum pressure lag in any test configuration. Again, a calibration was compared with calibrations of previous days.

Test Run.--After all calibrations had been completed, the following steps were taken in preparation for each test run:

1. The diaphragm section was assembled.

2. The system downstream from the diaphragm section was evacuated to approximately 0.20 mm of Hg after which the pumps were shut out of the system while the test line remained at atmospheric pressure.

3. The copper leads from the platinum elements were connected into the relay circuit.

4. The oil pan was filled, submerging the diaphragm section and the downstream end of the test line.

5. The time for energizing each platinum element was set in the relay circuit.

6. The recorders were started.

7. The test run was then begun by turning the relay circuit on.

8. The test run was stopped when the absolute pressure level in the test line was below 1.0 mm of Hg.

Detailed procedures used in performing the testing are given by Cremin (1).

Data Reduction.--Absolute pressure and pressure lag were read directly from the recorder trace in terms of counts. These counts were then converted to pressure in mm of Hg through the use of the calibration data. Graphs of absolute pressure and pressure lag versus time were plotted for each test run. These graphs were cross-plotted to obtain the effect of line length and line inside diameter on pressure lag.

CHAPTER IV

RESULTS

The trajectories presented in this report were supplied by the Army Ballistic Missile Agency, Huntsville, Alabama. Four discontinuities in the derivative existed in these trajectories. Duplicating the trajectories experimentally gave rise to impulses in the pressure lag at each discontinuity. Fig. 3 shows an example of these impulses. This investigation simulates a multi-stage missile with each stage of the missile firing at a prescribed time in flight, thus giving rise to the discontinuities in the derivative of the trajectory. A single-stage missile would have a single discontinuity (at $t = 0$) in the derivative in its trajectory. Thus, the impulses occurring at positions 2, 3, and 4 (Fig. 3) would yield conservative values for single-stage trajectories. Qualitative information regarding the pressure lag during the flight of a single-stage missile may therefore be obtained from this investigation.

Effect of Trajectory.--The experimental data is presented in four sets of figures, one set for each trajectory. It was difficult to obtain the effect of trajectory quantitively due to repeatability errors in the relay circuit which yielded slightly different trajectories for the same orifice plate. Qualitatively, the results indicate an increase in pressure lag with an increase in trajectory or the rate of change of the absolute pressure, applicable only to each separate trajectory.

Trajectory Nos. 1, 2, 3, and 4 are given in Figs. 3, 11, 19, and 27, respectively. The trajectory curves are mean values of the experimental data. All trajectories fall within a band ±1.0 per cent of the absolute pressure level. This scattered data for presumably similar trajectories is due to the previously mentioned error in the relay circuit.

<u>Effect of Inside Diameter</u>.--The effect of inside diameter on pressure lag with line length as parameter for trajectory Nos. 1, 2, 3, and 4 is given in Figs. 4-7, 12-15, 20-23, and 28-31, respectively. The pressure lag in the high vacuum range is accurate to ±0.1 mm of Hg and is represented by a broken line in all figures.

These figures indicate a small increase in pressure lag when changing from a 0.15625 inches to 0.125 inches inside diameter test line for all trajectories and constant lengths. However, a large increase in pressure lag occurs when changing from a 0.125 inches to a 0.0625 inches inside diameter test line.

<u>Effect of Length</u>.--Figs. 8-10, 16-18, 24-26, and 32-34 represent the effect of line length on pressure lag with line inside diameter as parameter for trajectory Nos. 1, 2, 3, and 4 respectively.

The above figures show that for constant line inside diameter the pressure lag varies approximately linearly with line length. For 0.125 and 0.15625 inches inside diameter a change of length has very little effect on the change in the magnitude of the pressure lag. A definite increase in the pressure lag is noticed when the length is increased for a 0.0625 inches inside diameter test line.

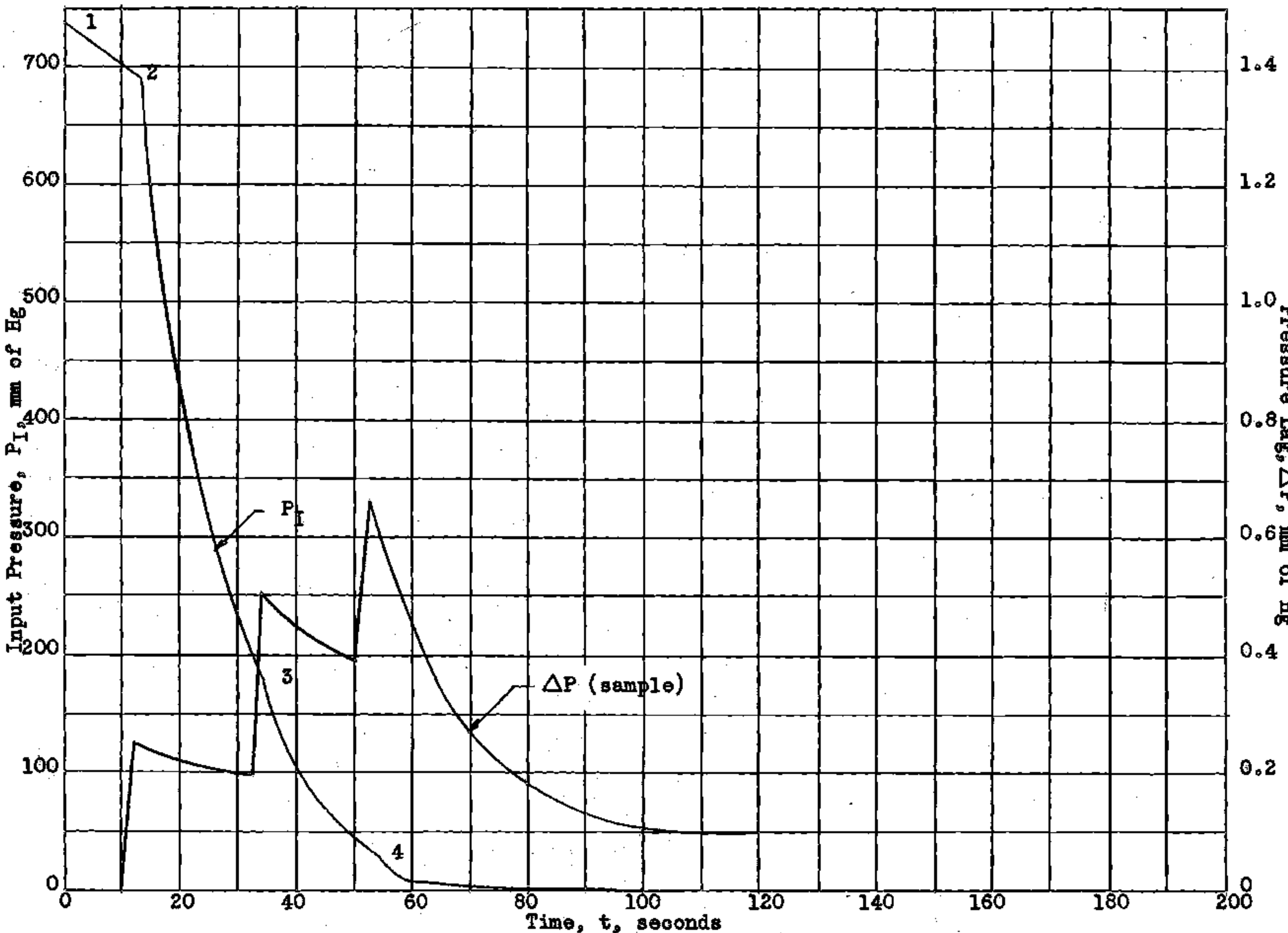


Fig. 3 Trajectory #1

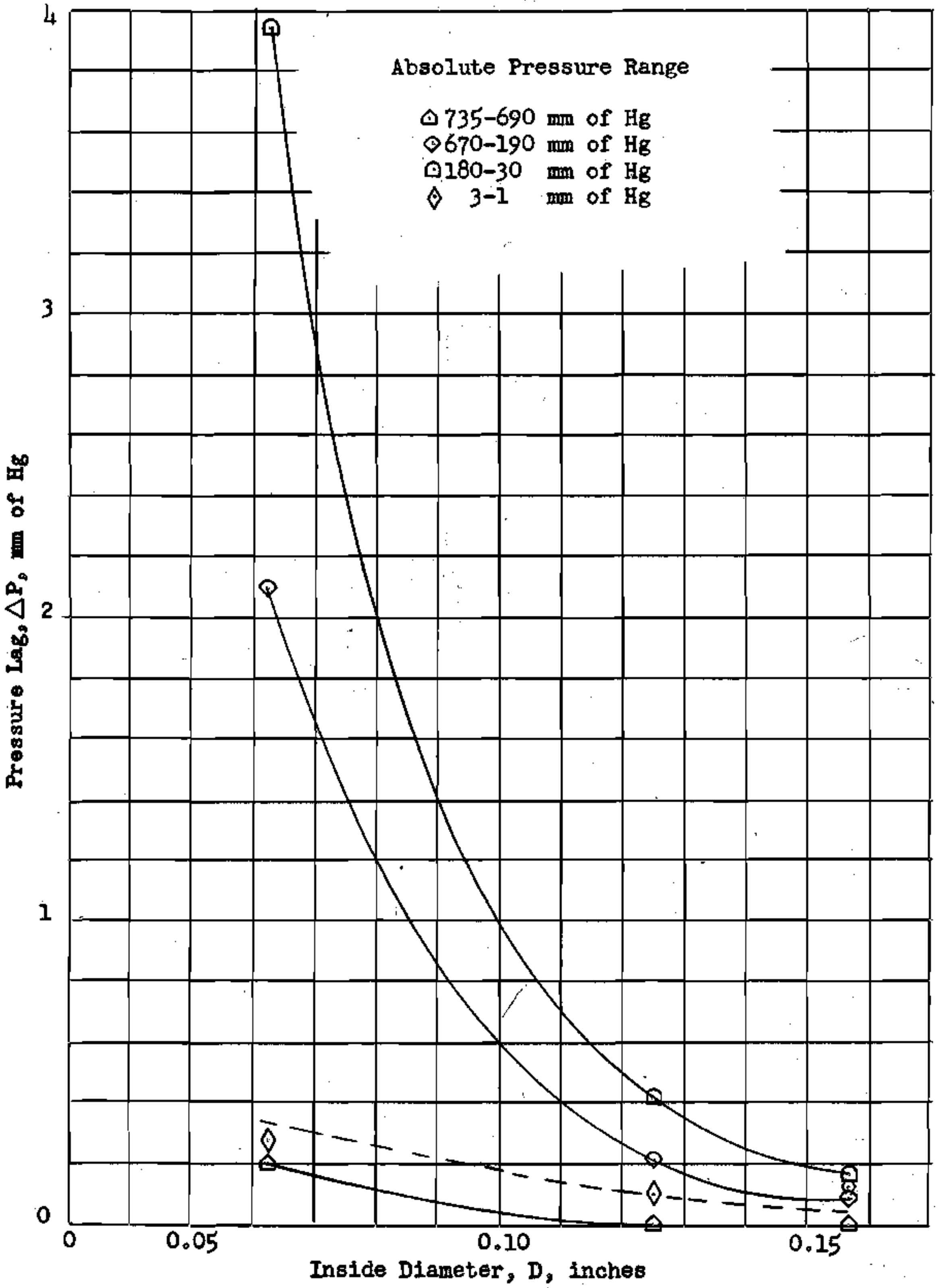


Fig. 4 Trajectory #1--Pressure Lag vs. Inside Diameter for a 75-inch Test Line

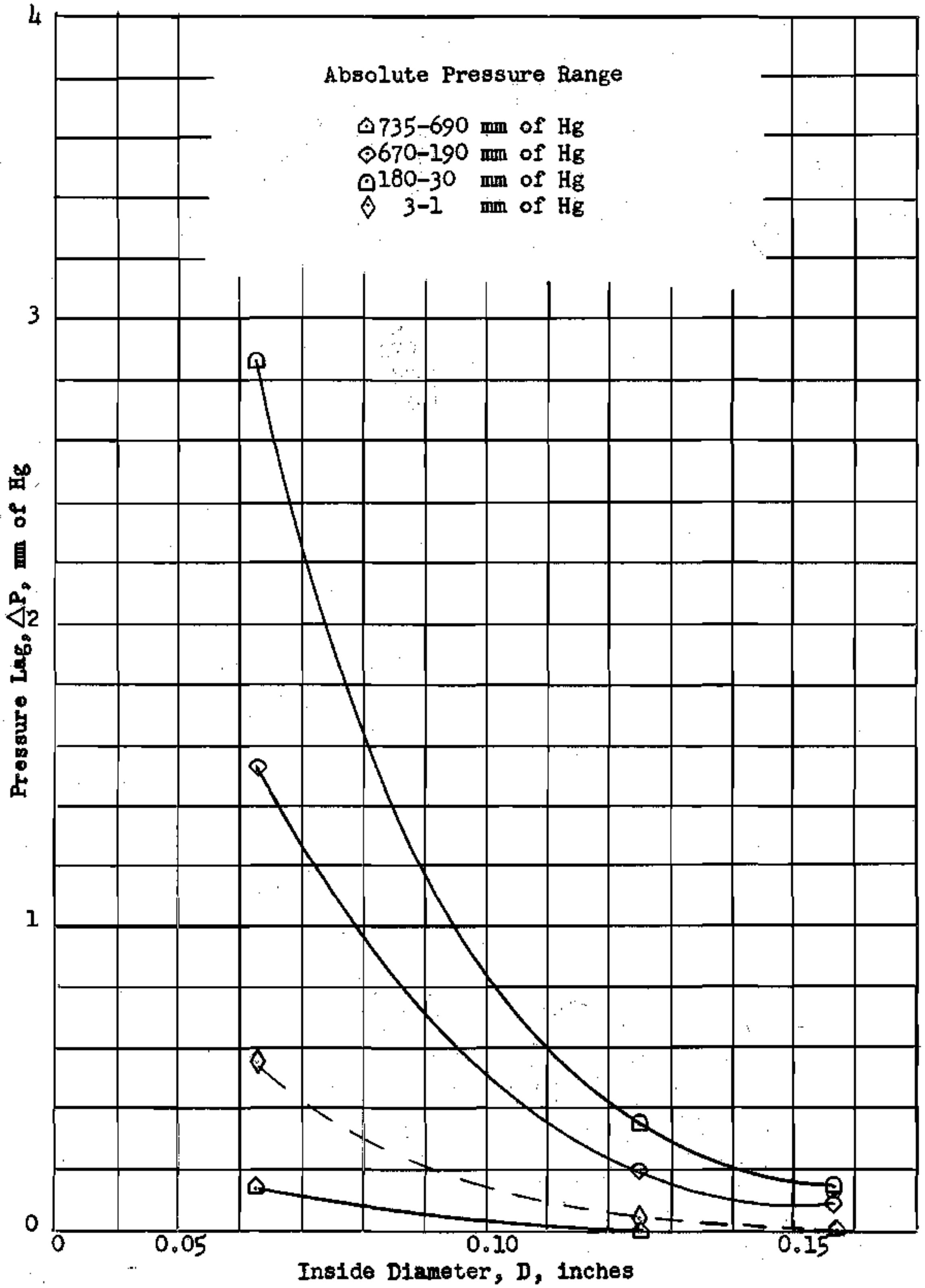


Fig. 5 Trajectory #1--Pressure Lag vs. Inside Diameter for a 60-inch Test Line

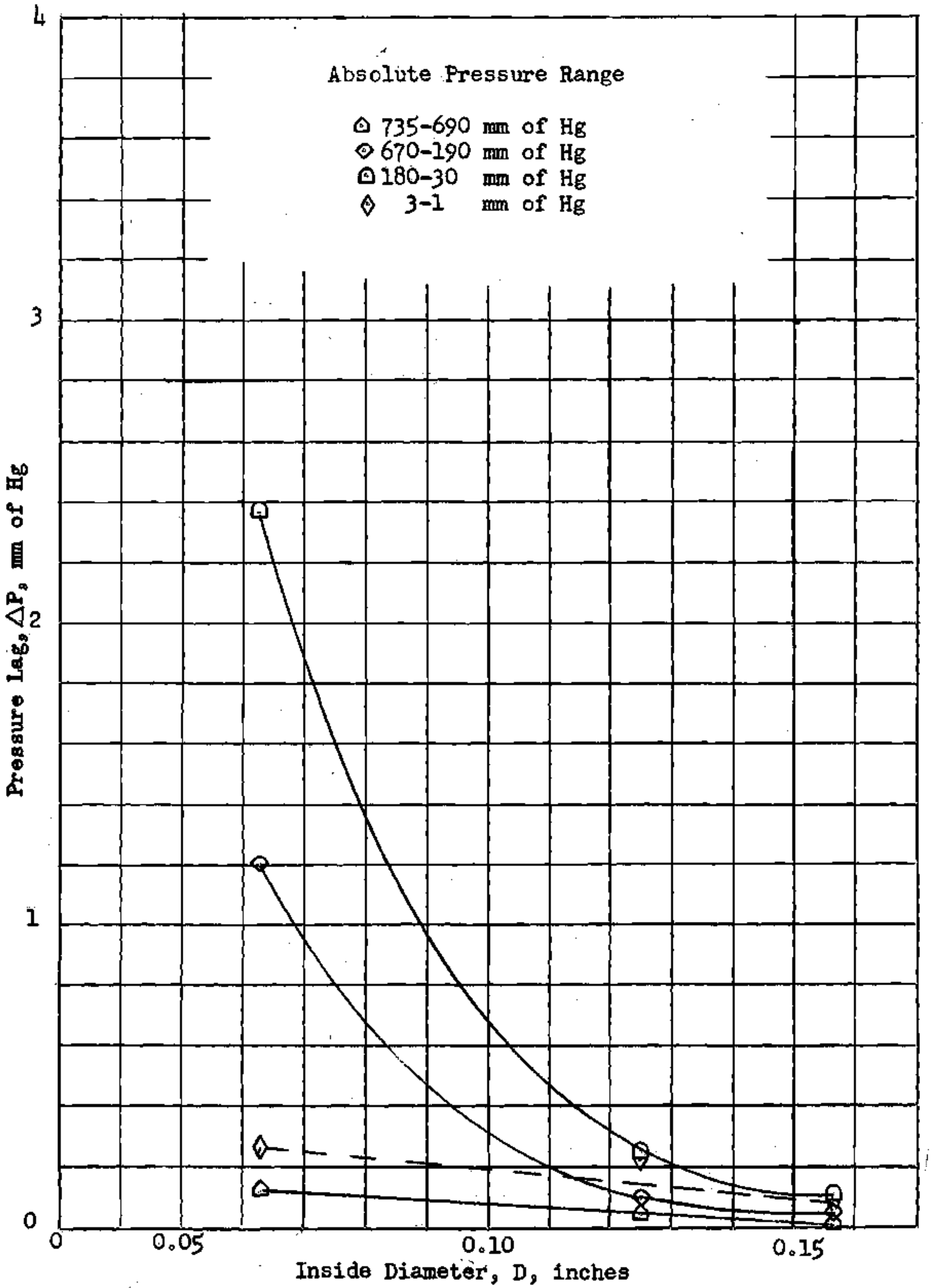


Fig. 6 Trajectory #1--Pressure Lag vs. Inside Diameter for 45-inch Test Line

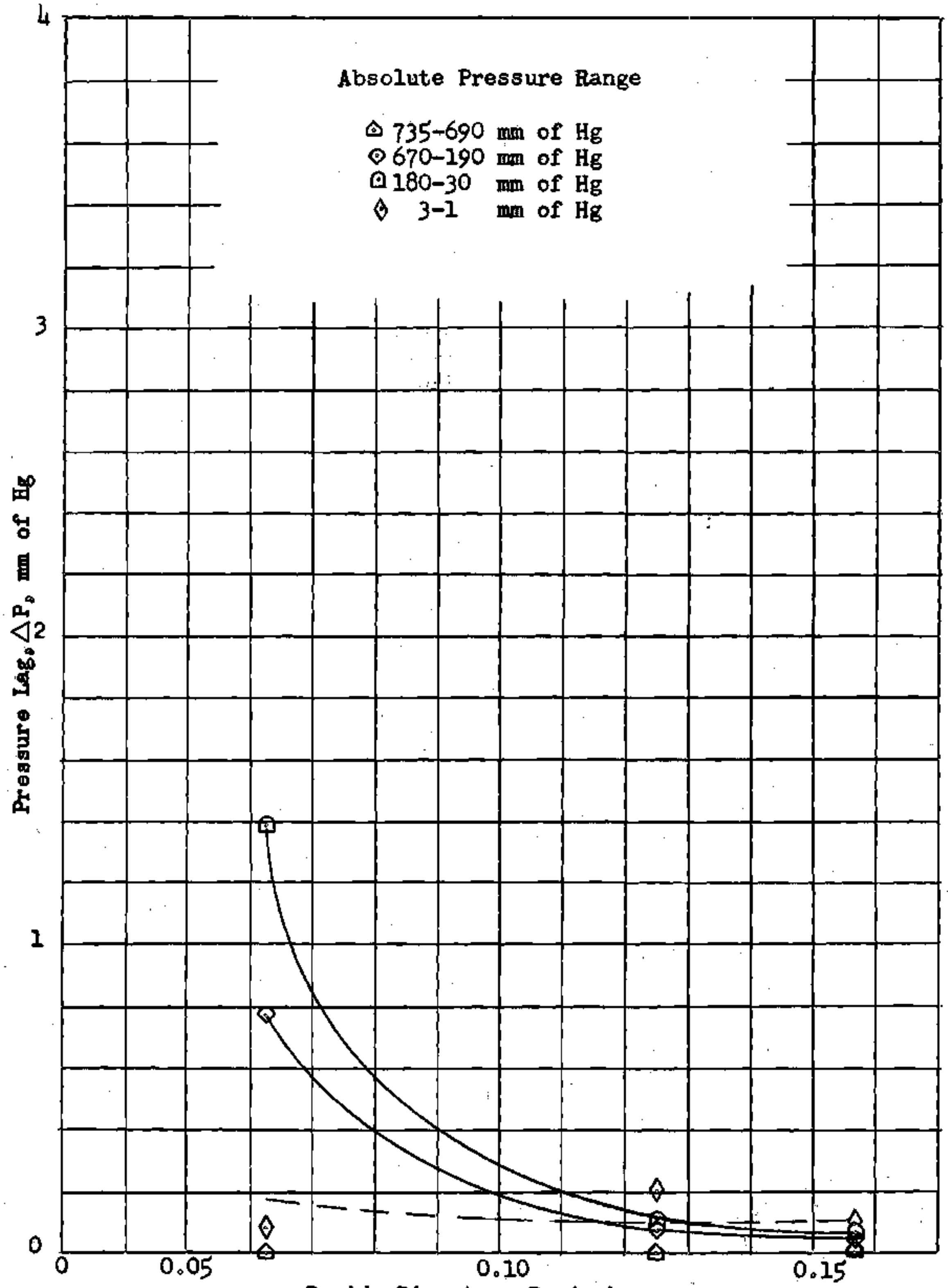


Fig. 7 Trajectory #1--Pressure Lag vs. Inside Diameter for 30-inch Test Line

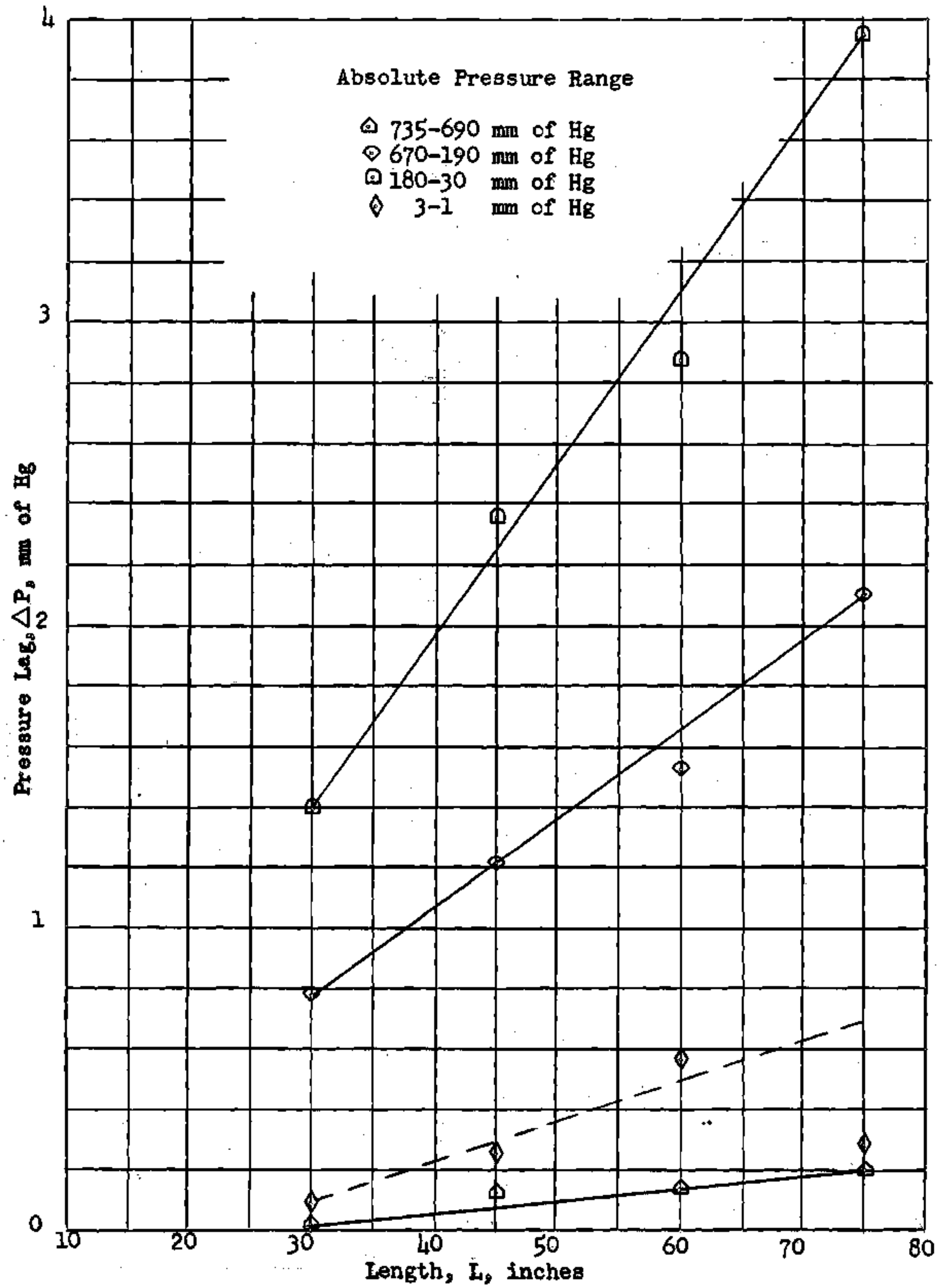


Fig. 8 Trajectory #1--Pressure Lag vs. Length for an Inside Diameter of 0.0625-inch Test Line

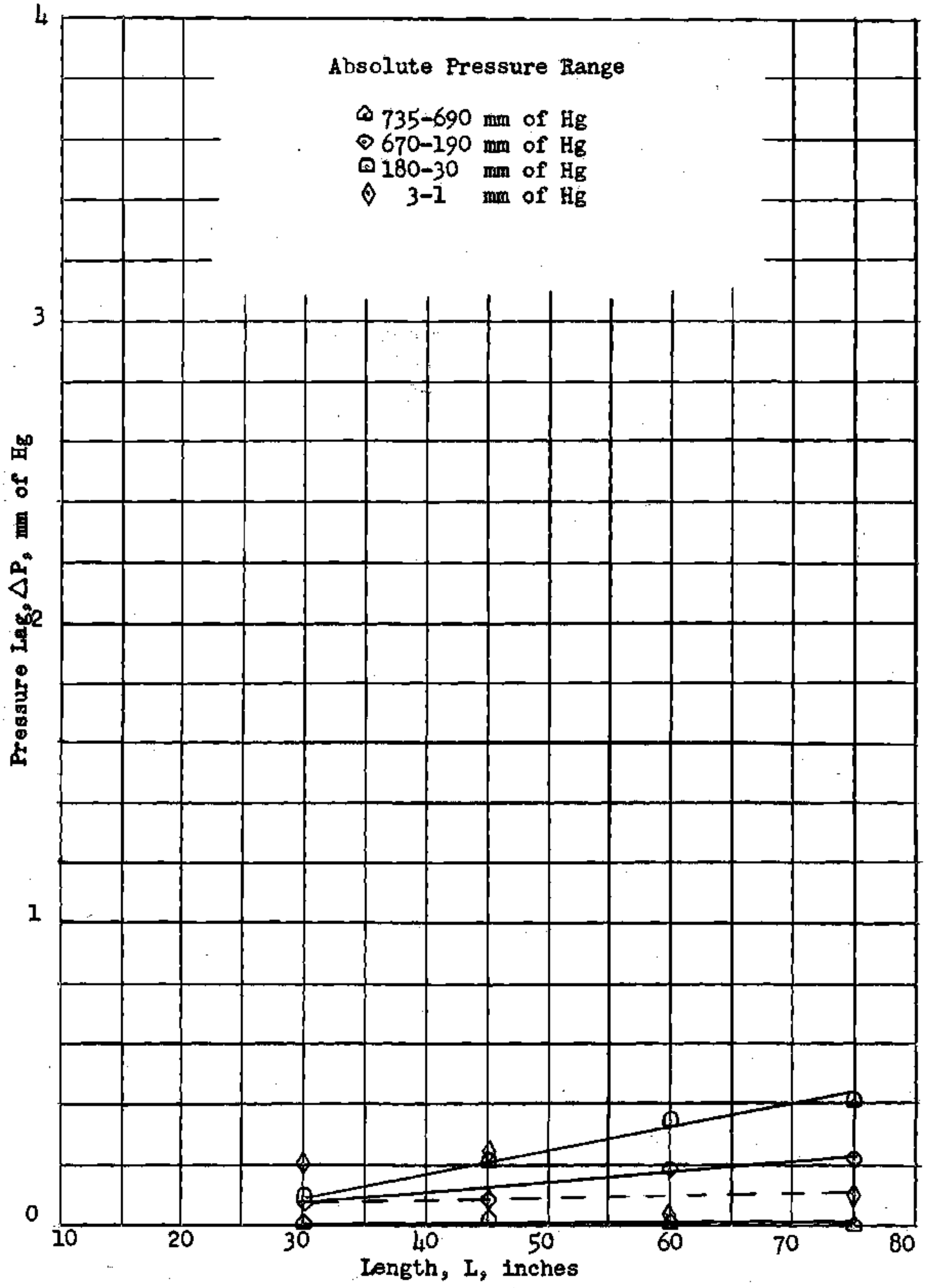


Fig. 9 Trajectory #1--Pressure Lag vs. Length for an Inside Diameter of 0.125-inch Test Line

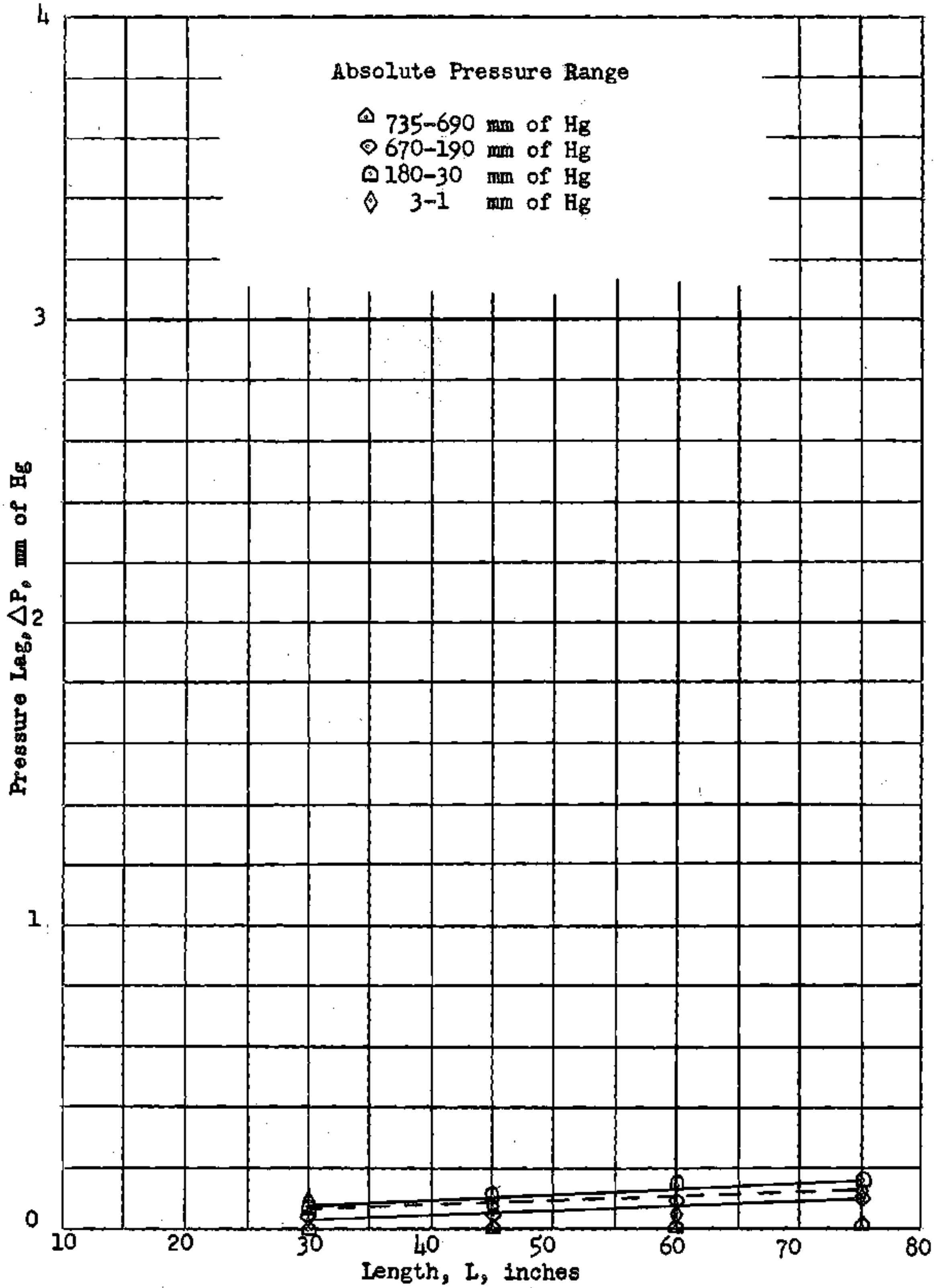


Fig. 10 Trajectory #1--Pressure Lag vs. Length for an Inside Diameter of 0.15625-inch Test Line

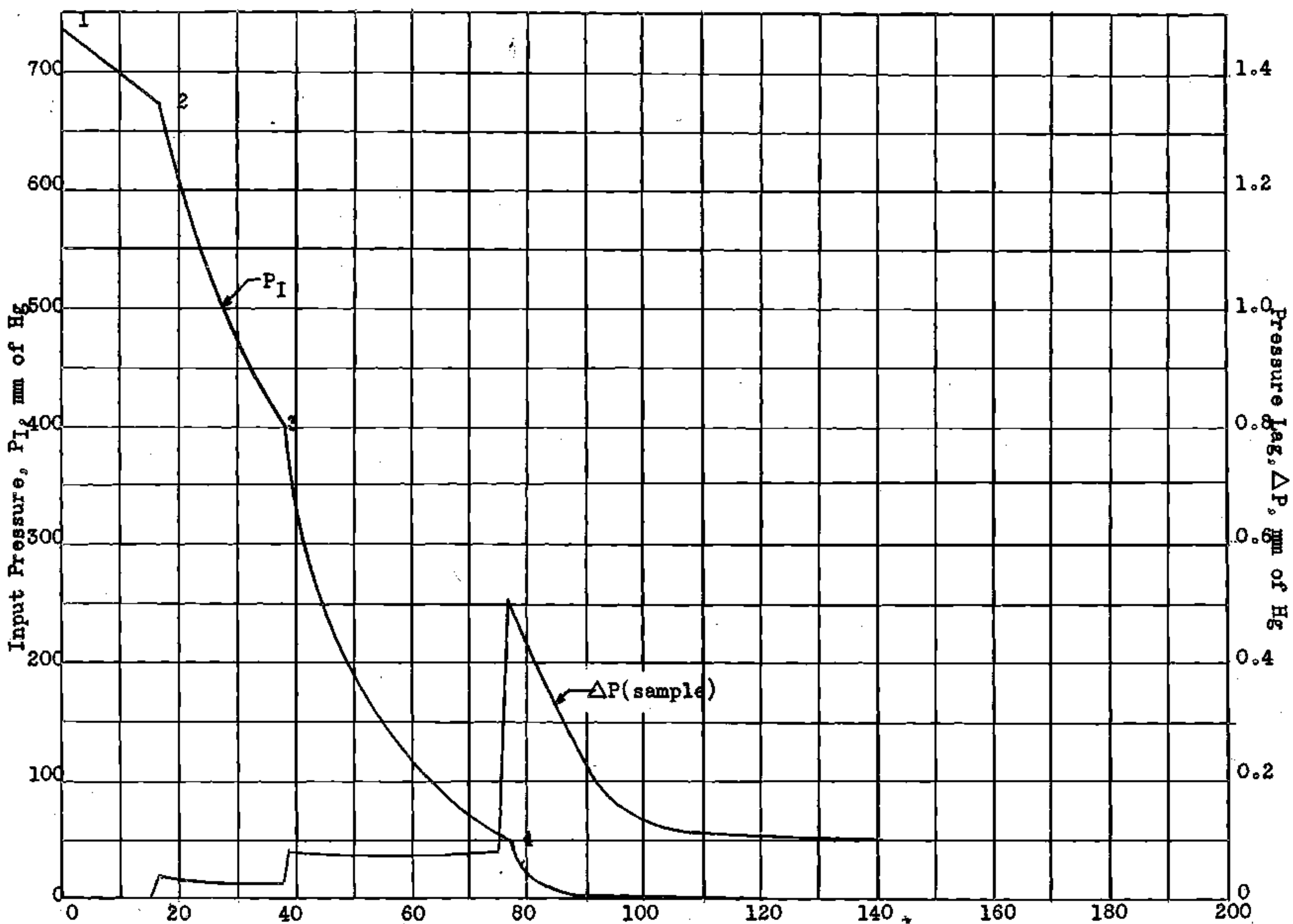


Fig. 11 Trajectory #2

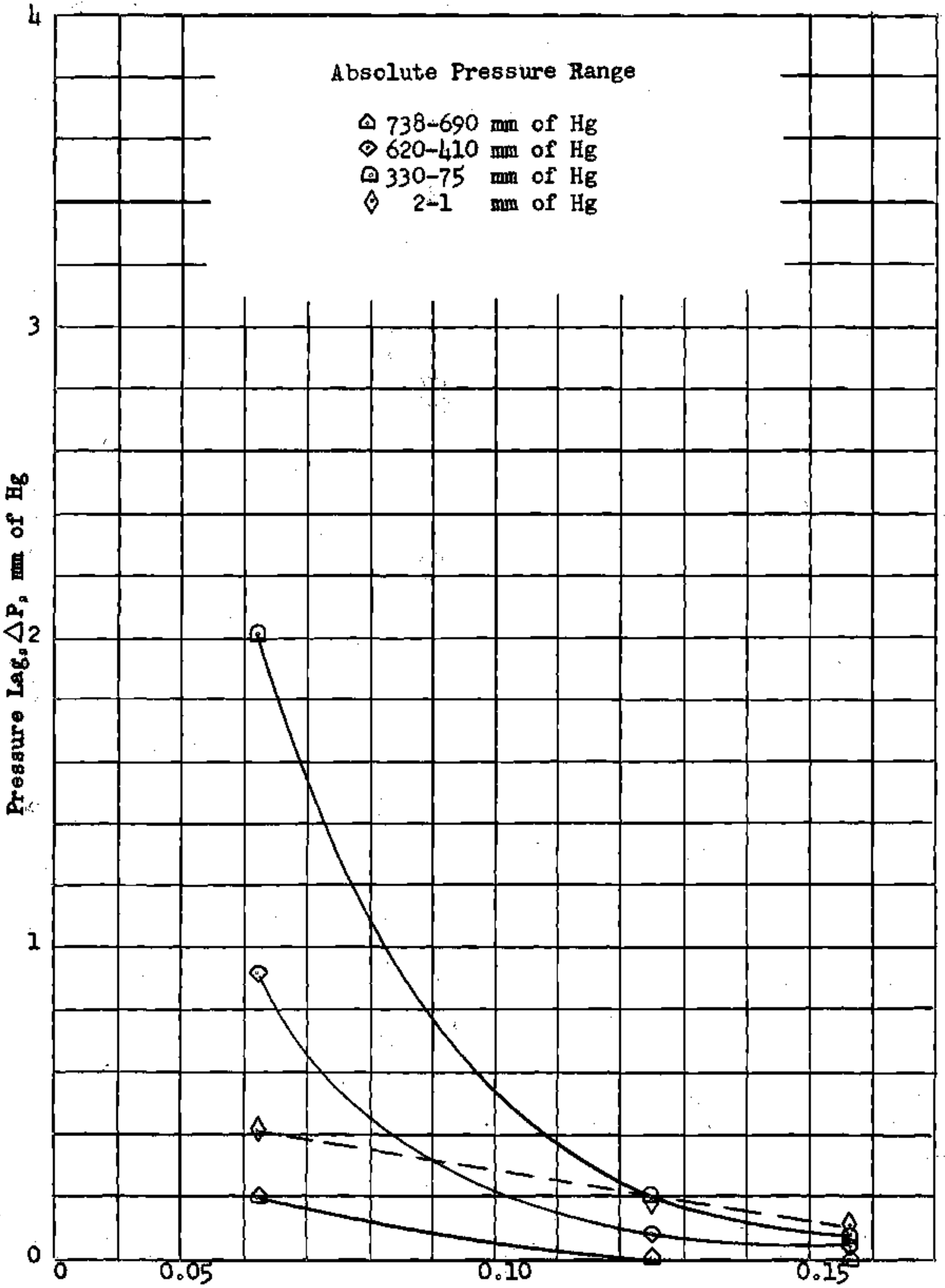


Fig. 12 Trajectory #2--Pressure Lag vs. Inside Diameter for 75-inch Test Line

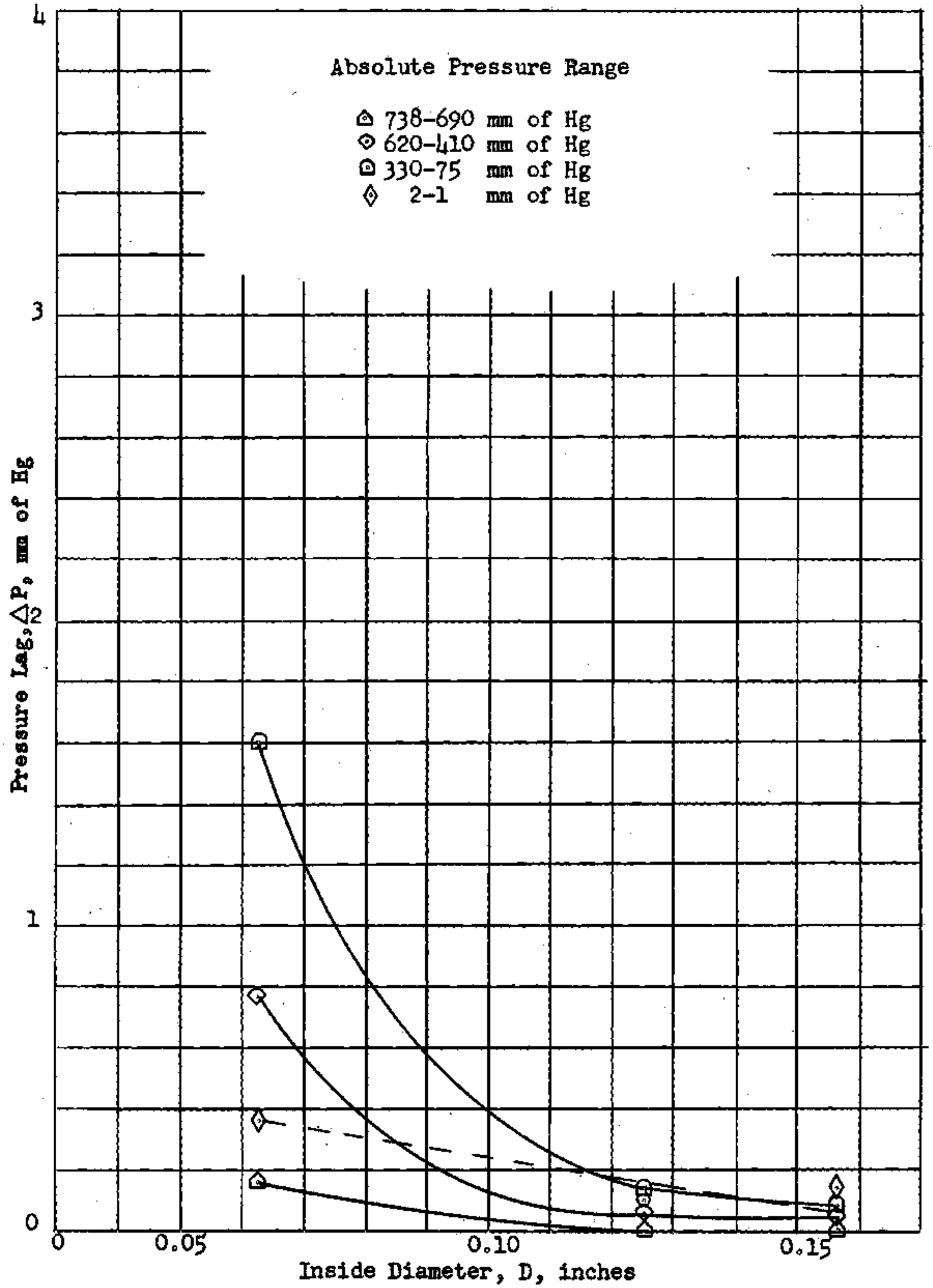


Fig. 13 Trajectory #2--Pressure Lag vs. Inside Diameter for 60-inch Test Line

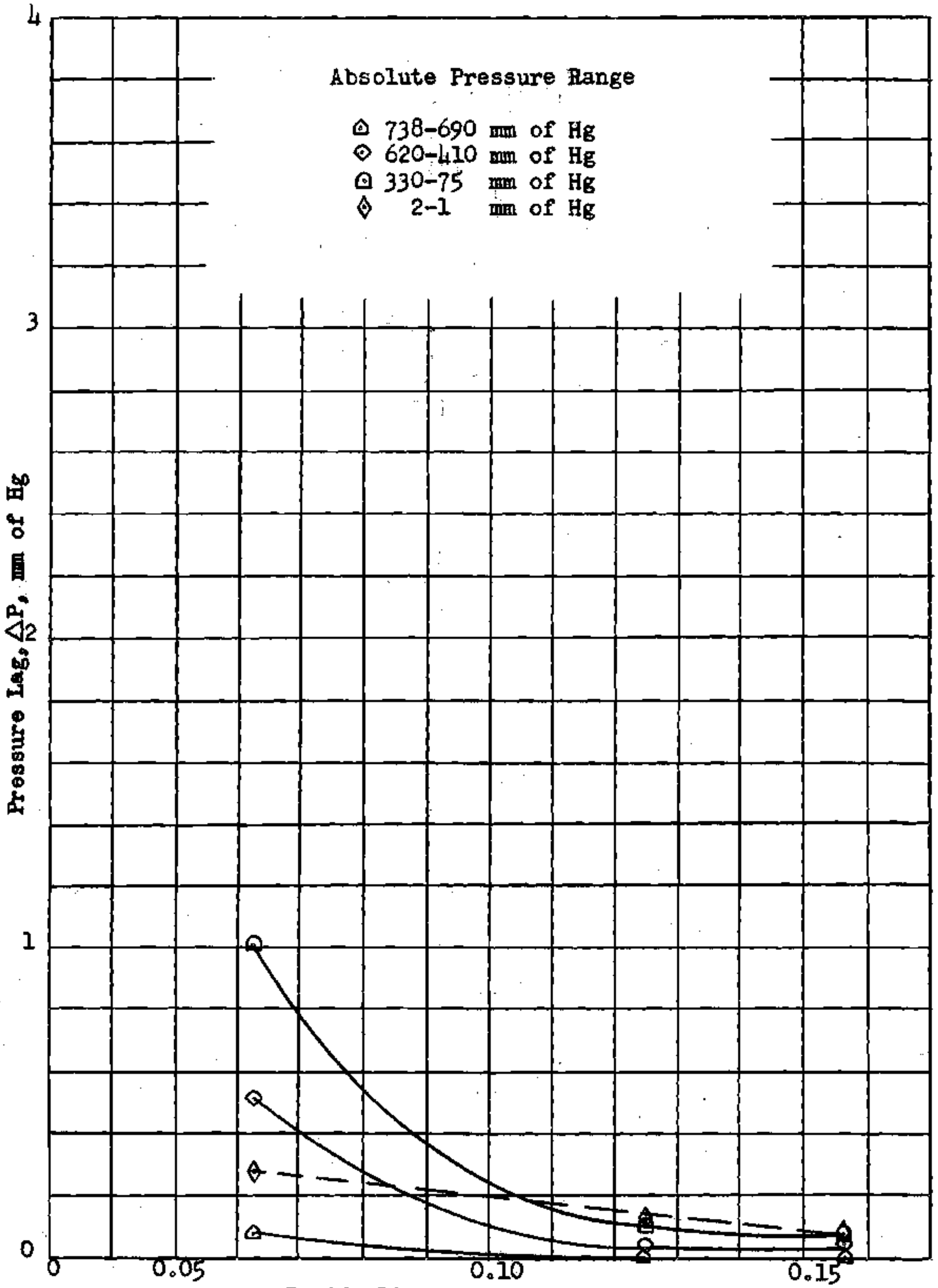


Fig. 14 Trajectory #2--Pressure Lag vs. Inside Diameter for 45-inch Test Line

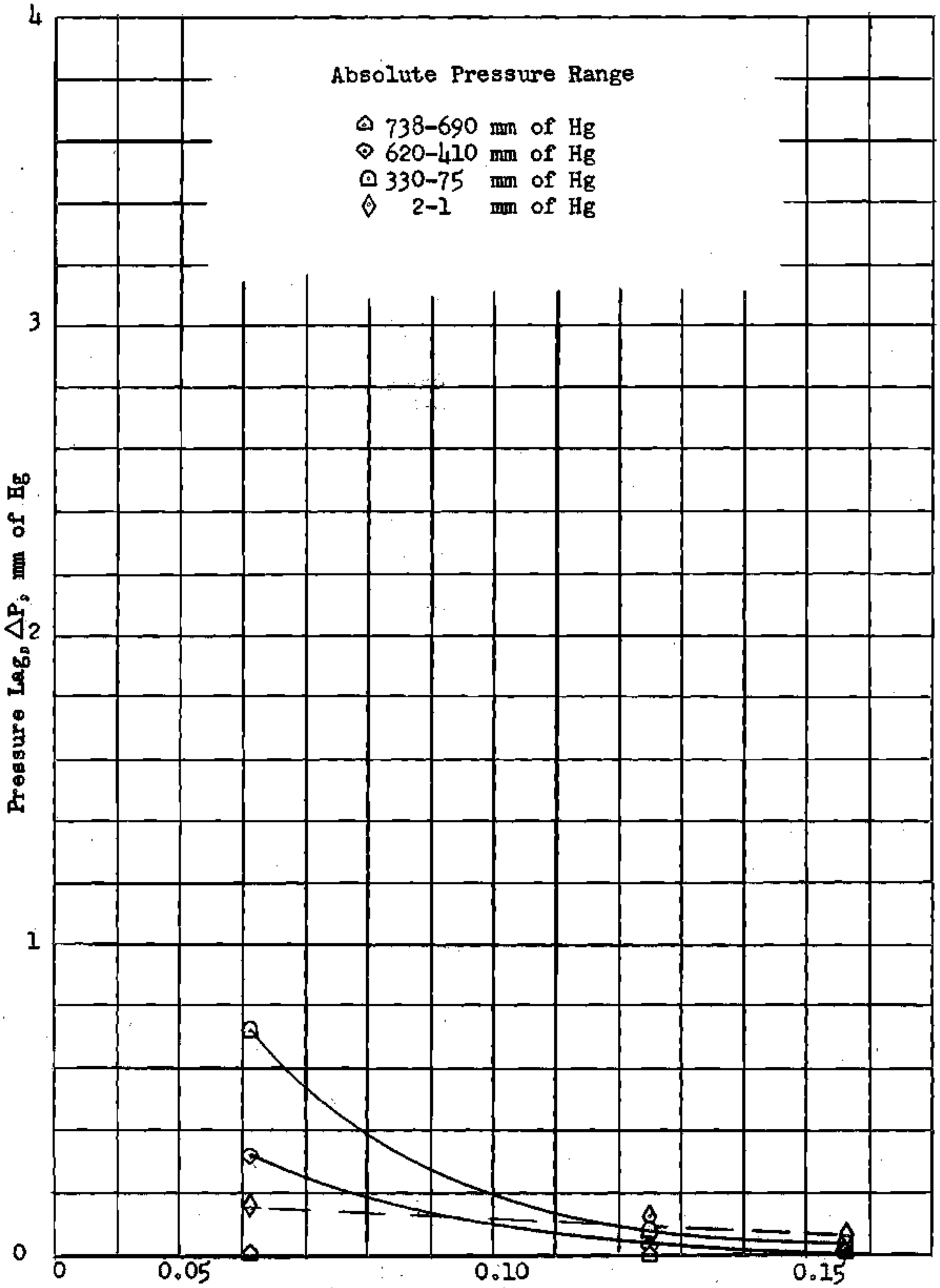


Fig. 15 Trajectory #2--Pressure Lag vs. Inside Diameter for 30-inch Test Line

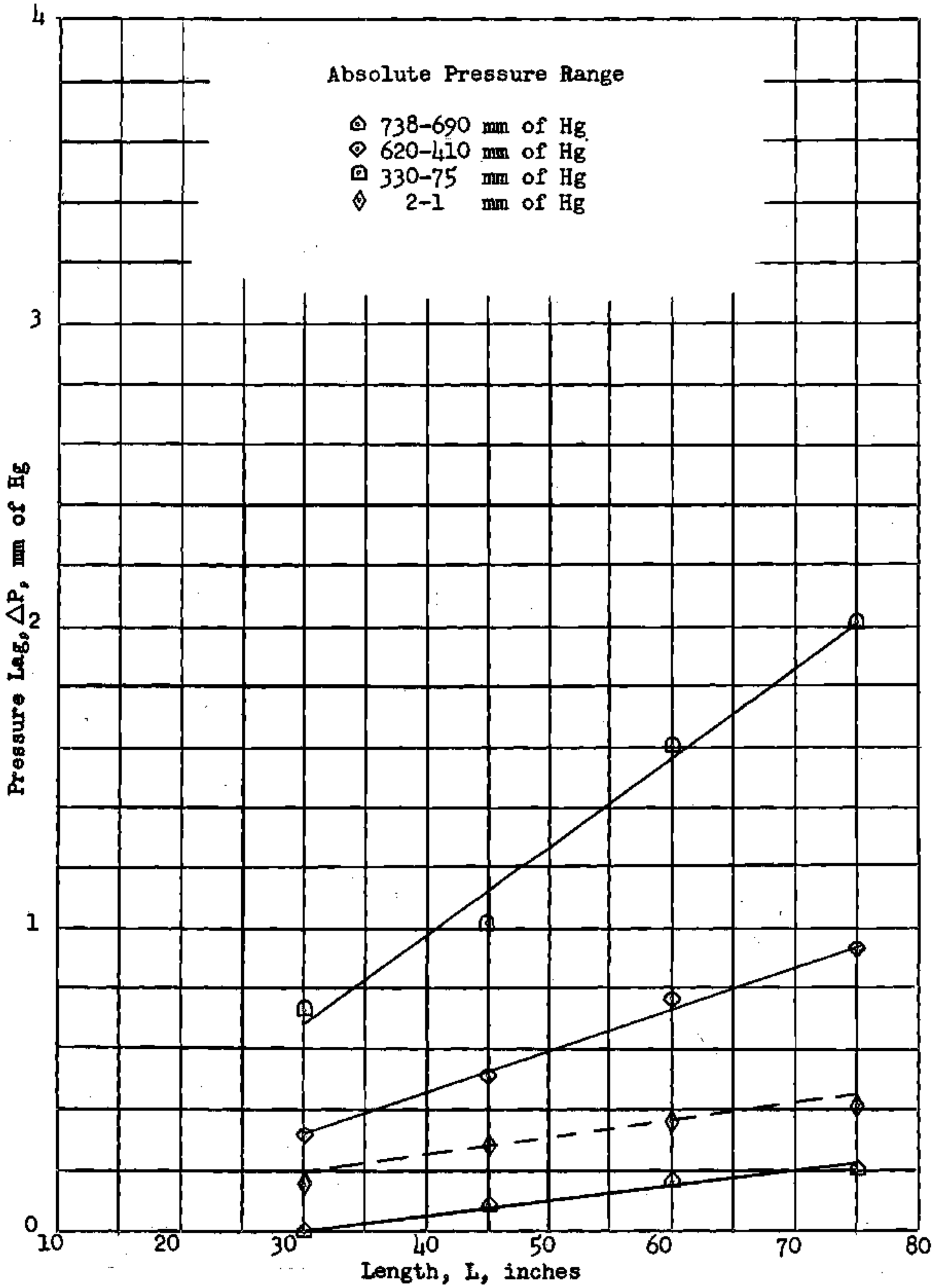


Fig. 16 Trajectory #2--Pressure Lag vs. Length for an Inside Diameter of 0.0625-inch Test Line

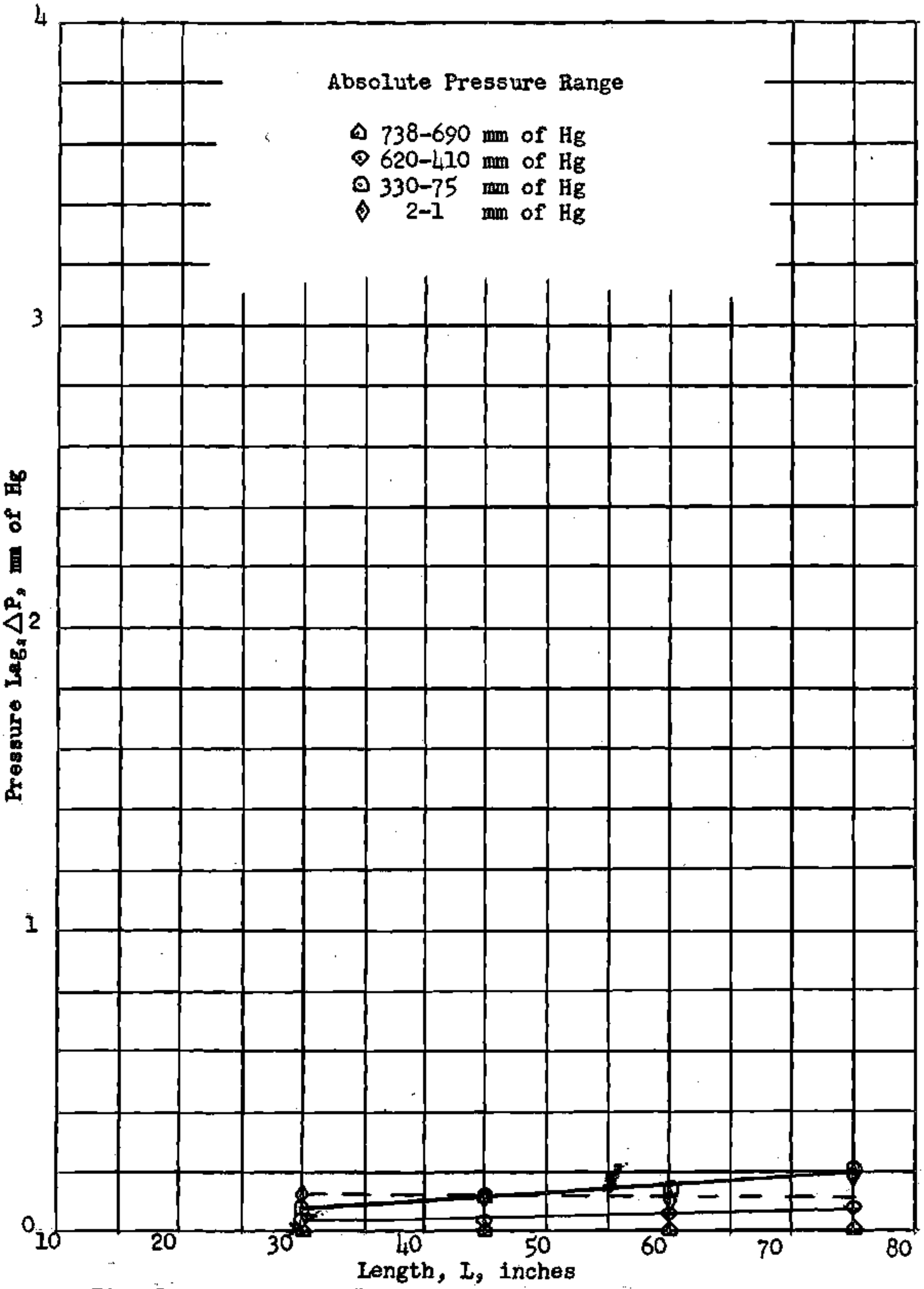


Fig. 17 Trajectory #2—Pressure Lag vs. Length for an Inside Diameter of 0.125-inch Test Line

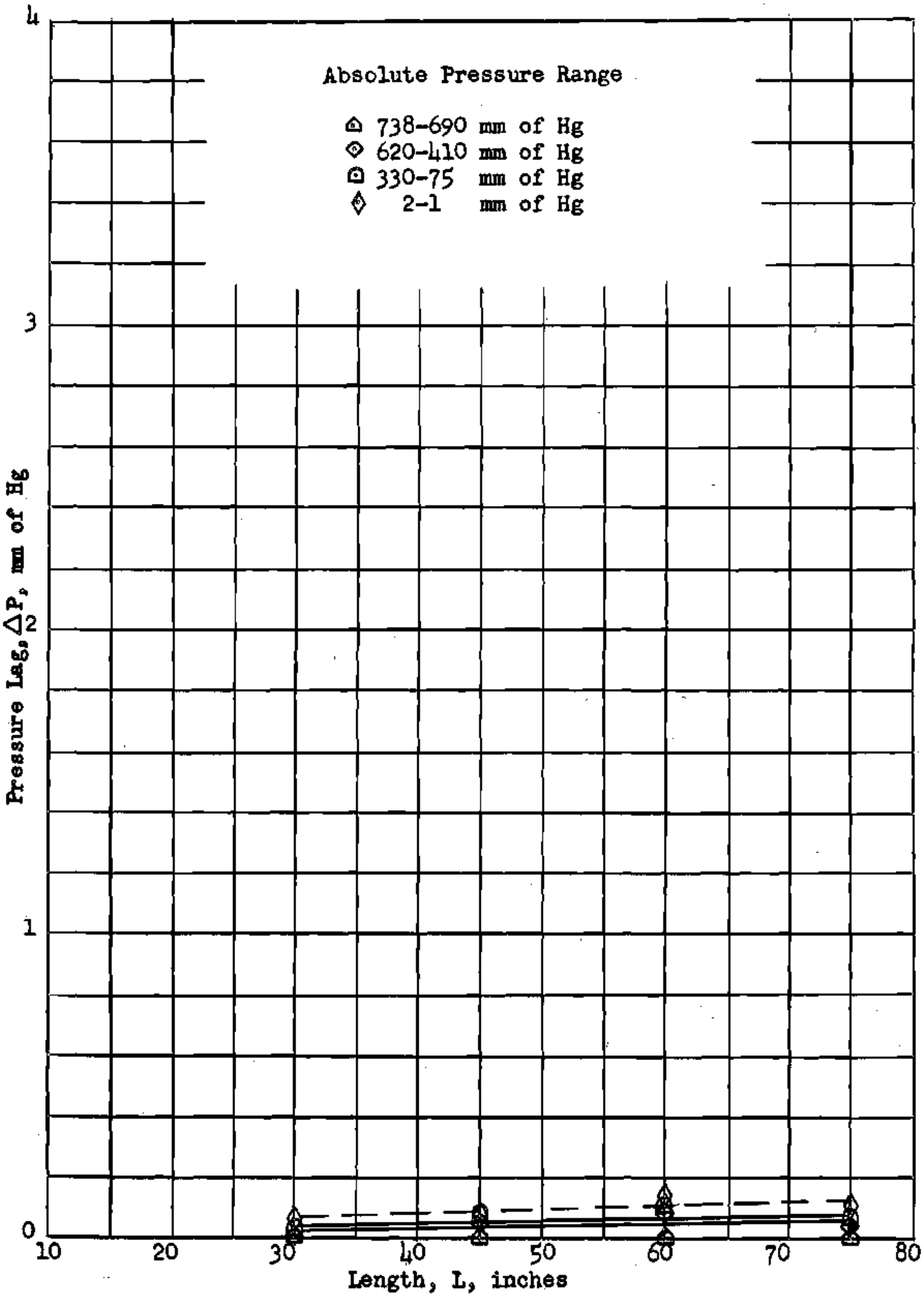


Fig. 18 Trajectory #2--Pressure Lag vs. Length for an Inside Diameter of 0.15625-inch Test Line

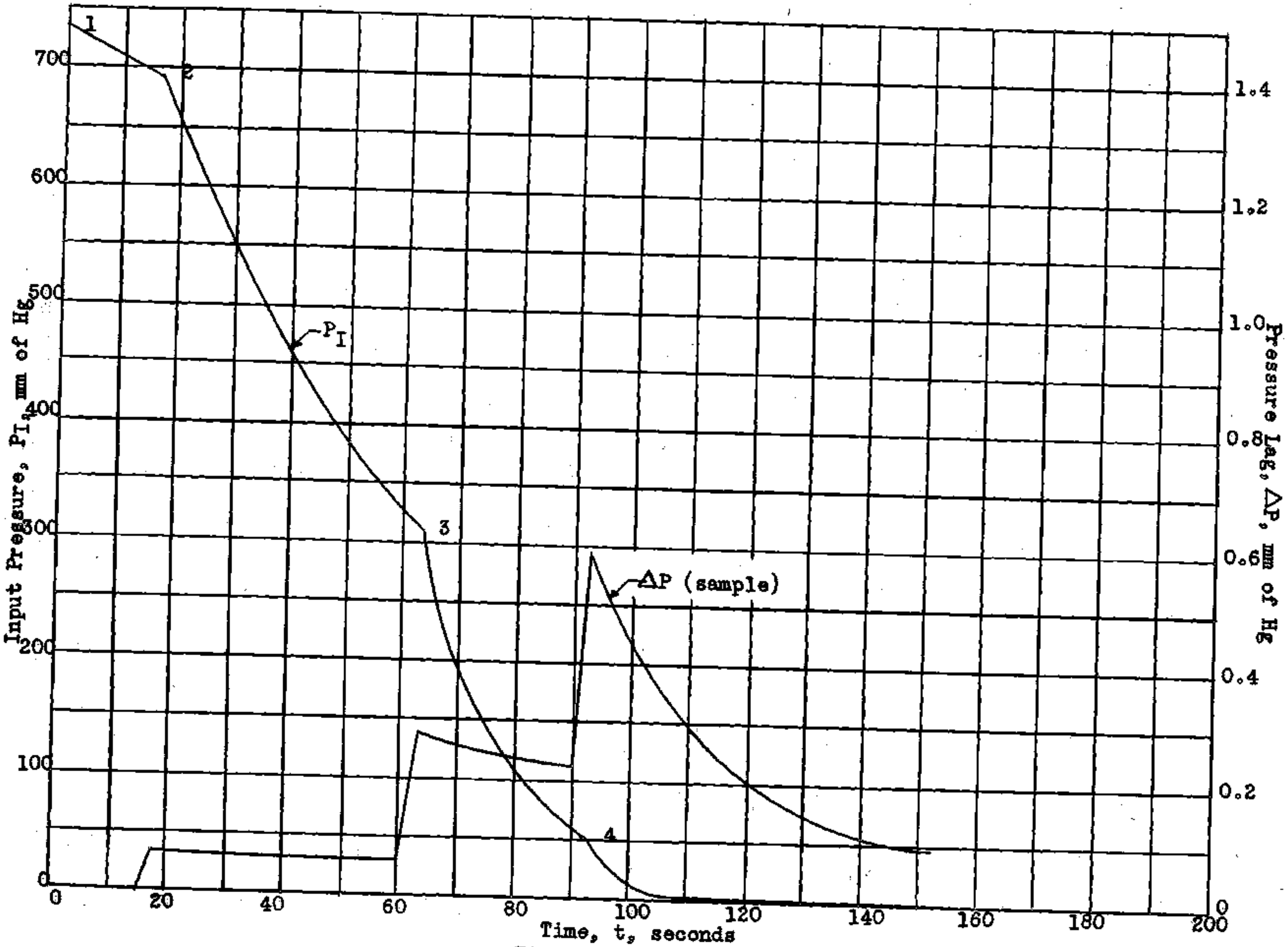


Fig. 19 Trajectory #3

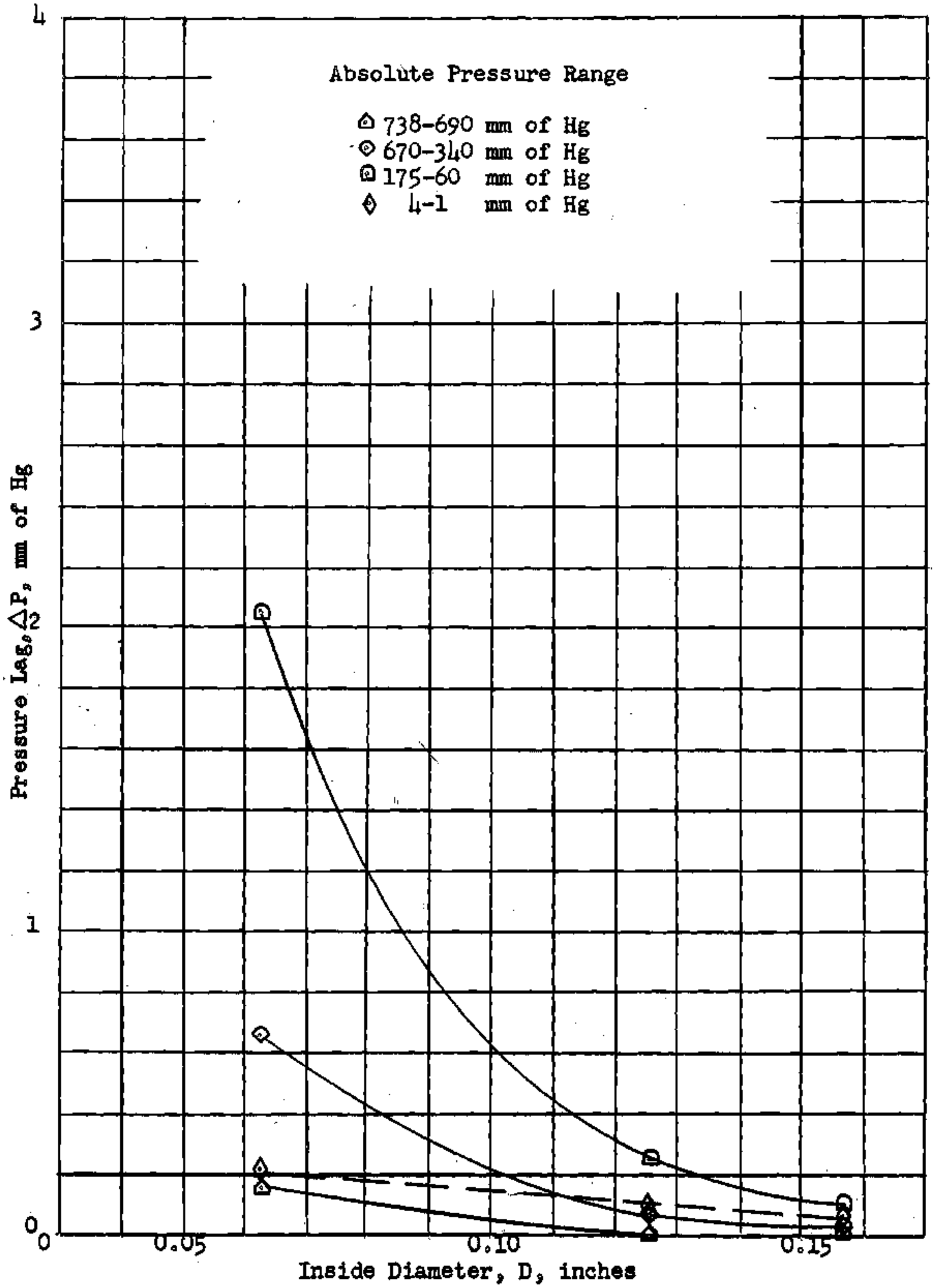


Fig. 20 Trajectory #3--Pressure Lag vs. Inside Diameter for 75-inch Test Line

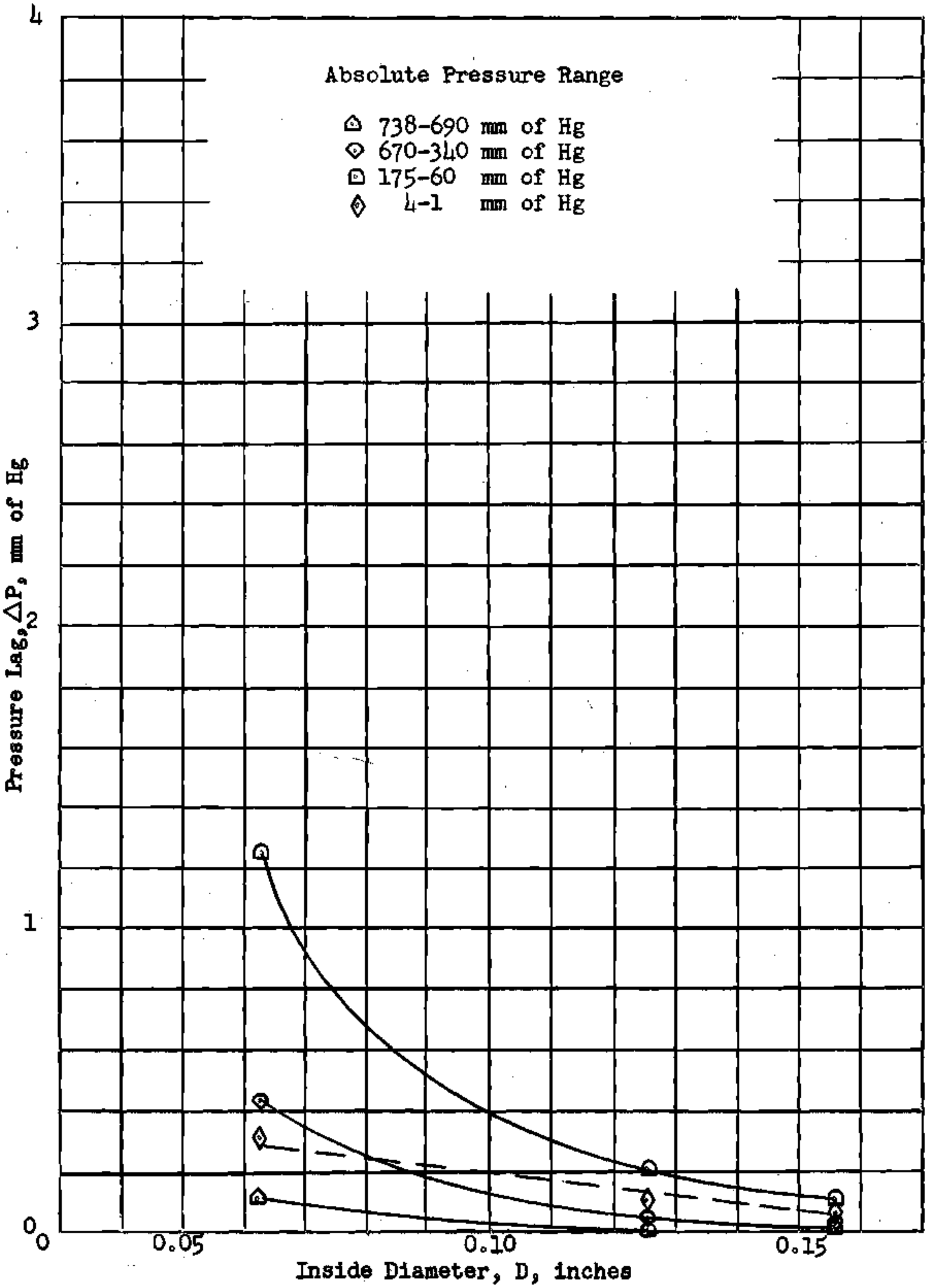


Fig. 21 Trajectory #3--Pressure Lag vs. Inside Diameter for 60-inch Test Line

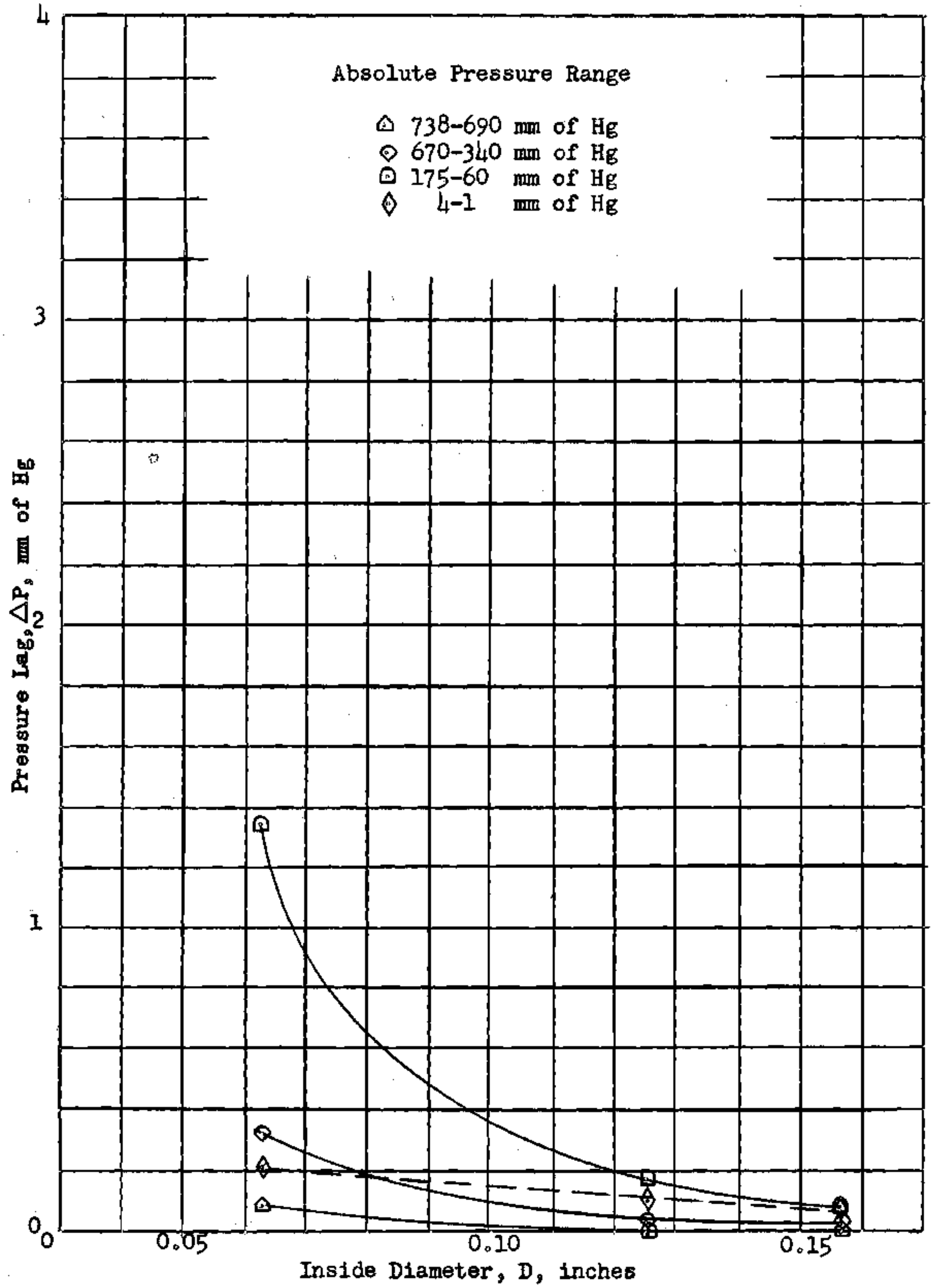


Fig. 22 Trajectory #3--Pressure Lag vs. Inside Diameter for 45-inch Test Line

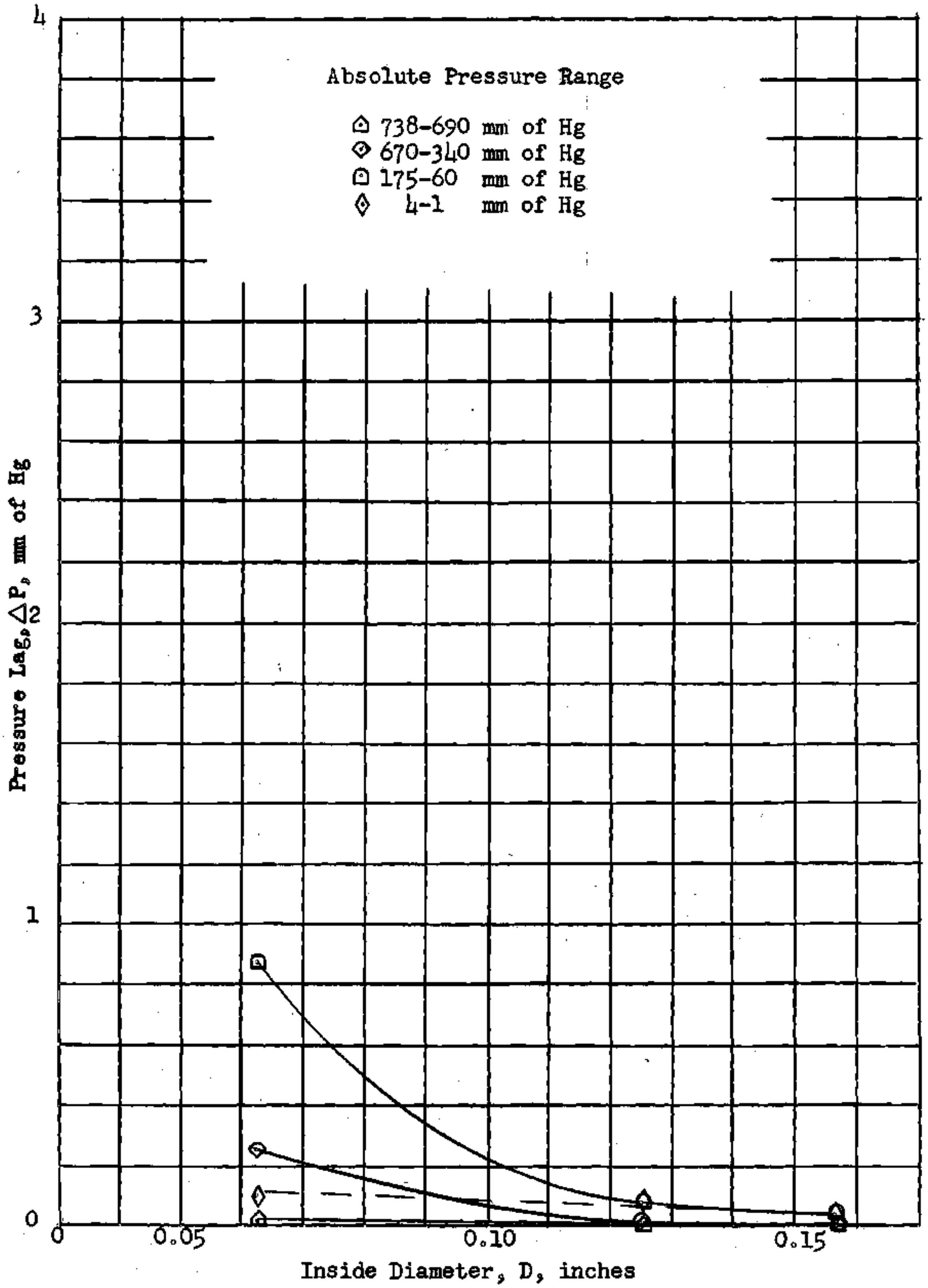


Fig. 23 Trajectory #3--Pressure Lag vs. Inside Diameter for 30-inch Test Line

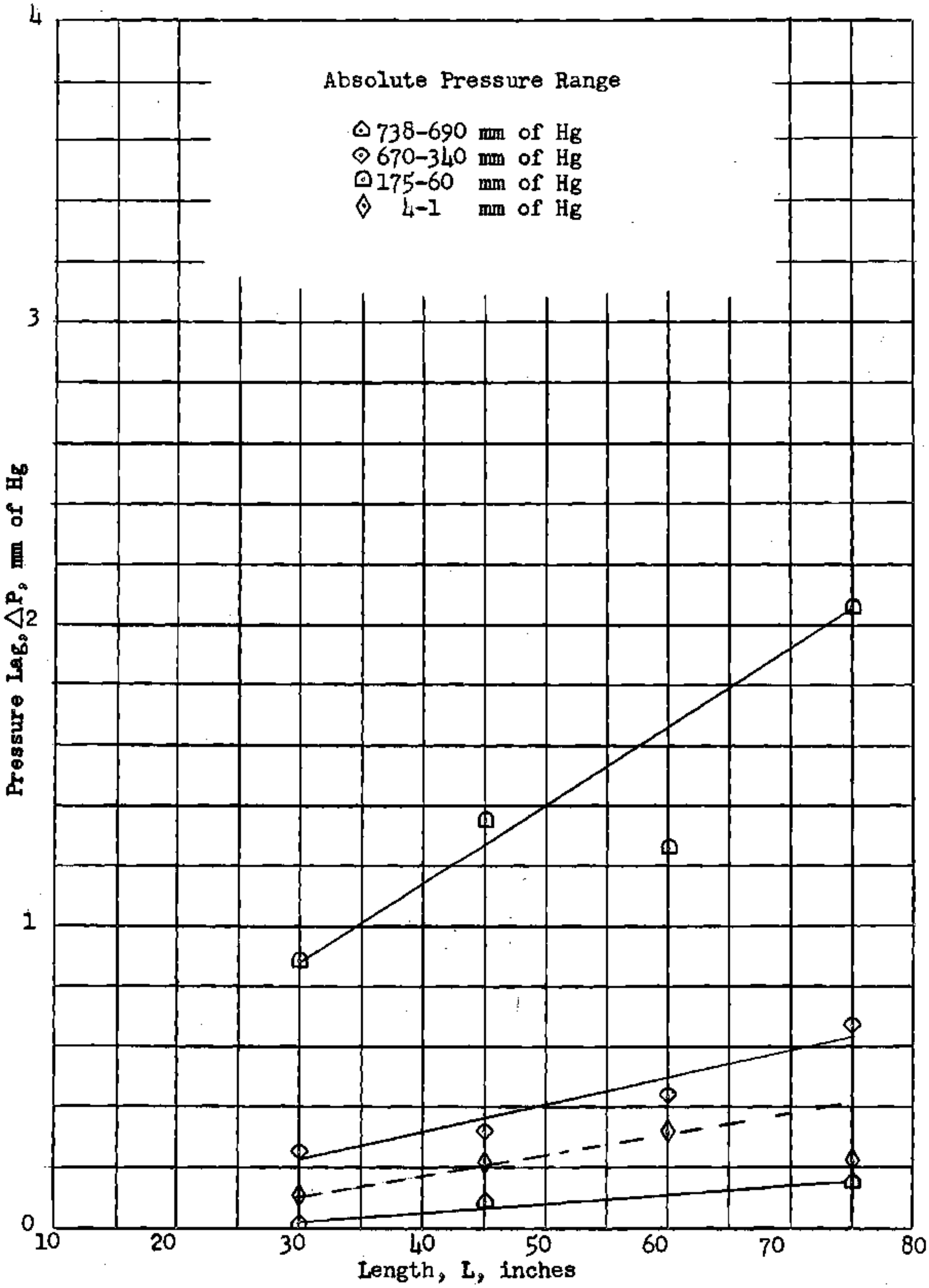


Fig. 24 Trajectory #3--Pressure Lag vs. Length for an Inside Diameter of 0.0625-inch Test Line

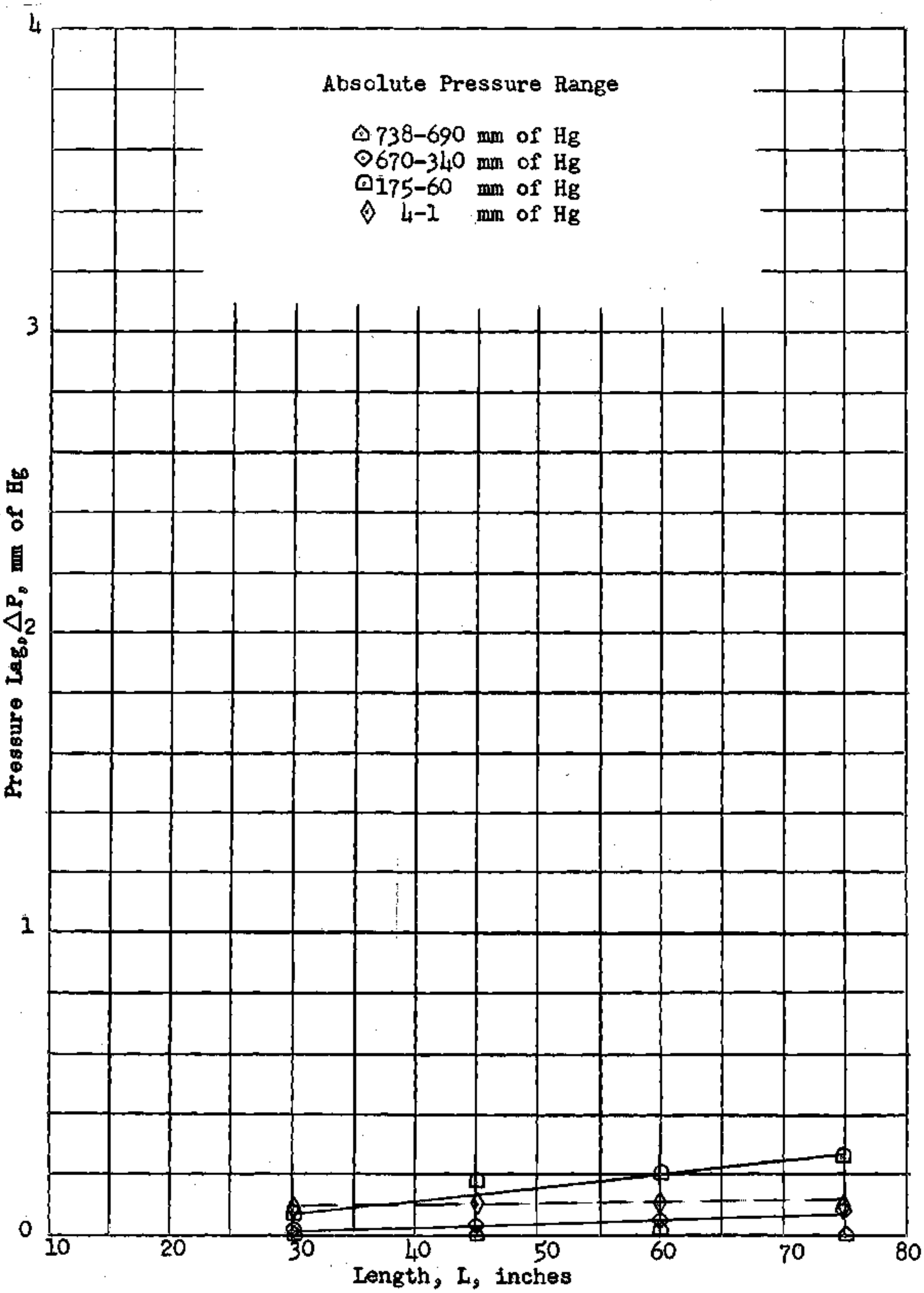


Fig. 25 Trajectory #3—Pressure Lag vs. Length for an Inside Diameter of 0.125-inch Test Line

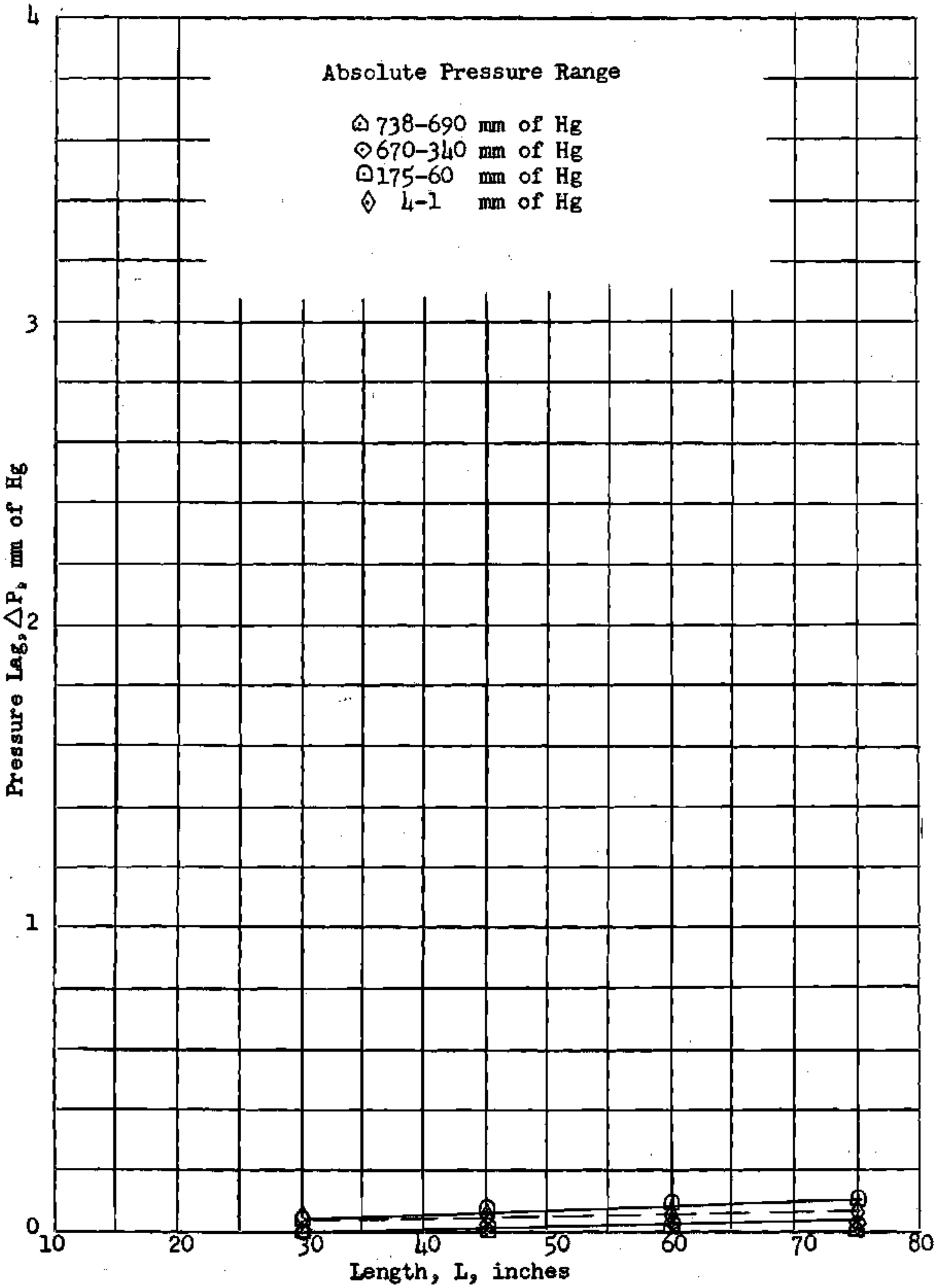
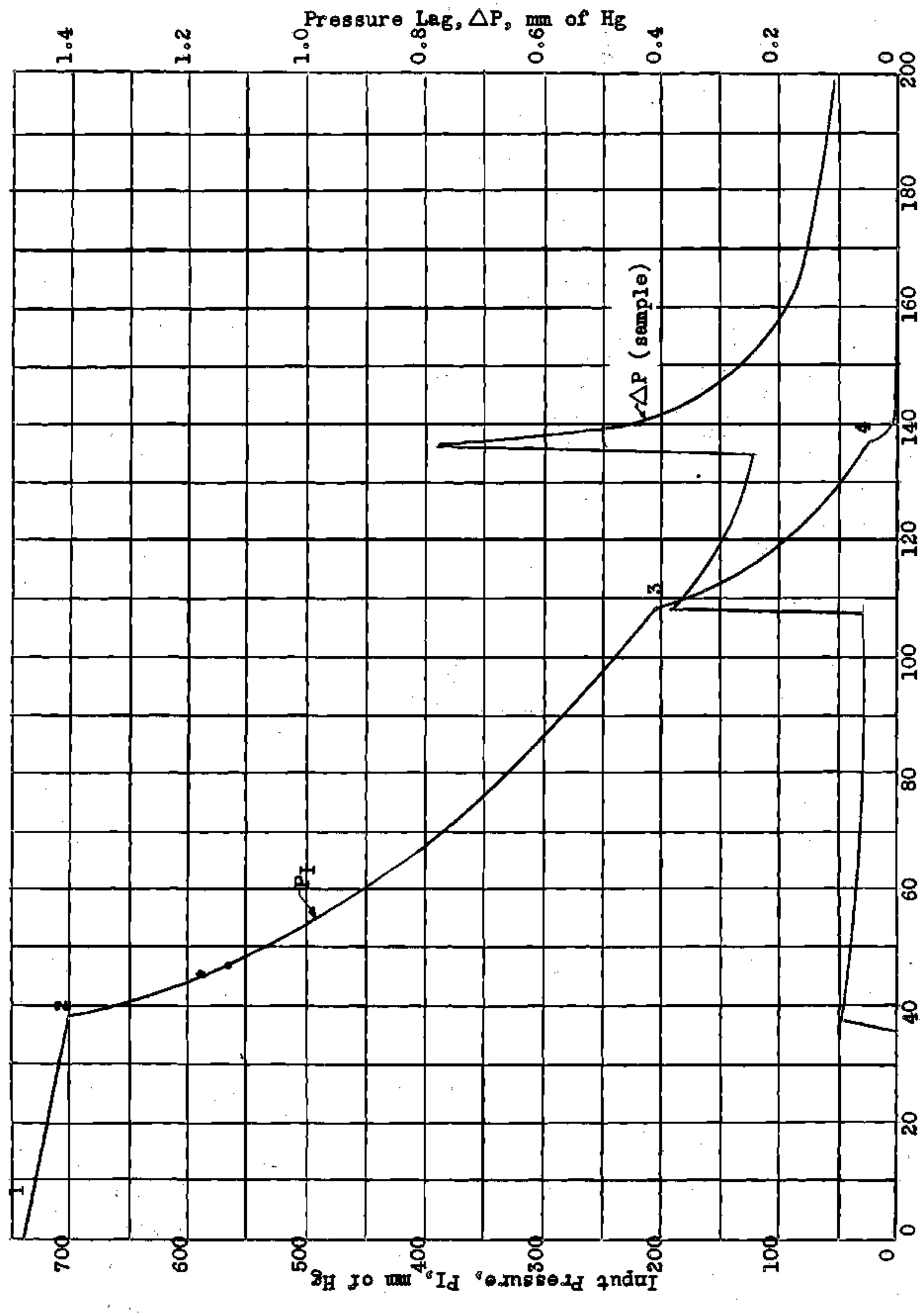


Fig. 26 Trajectory #3—Pressure Lag vs. Length for an Inside Diameter of 0.15625-inch Test Line



Time, t, seconds
Fig. 27 Trajectory #4

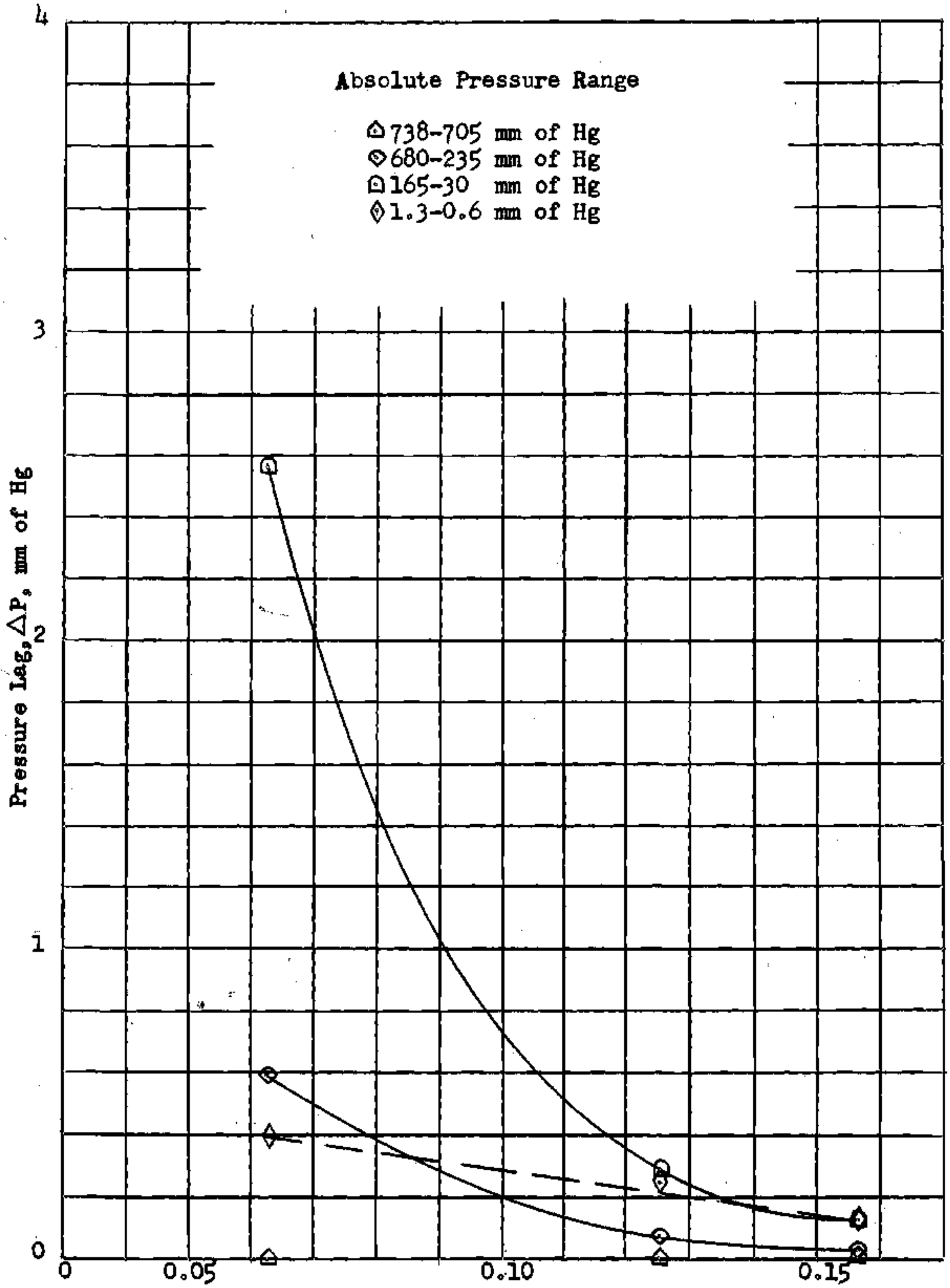


Fig. 28 Trajectory #4—Pressure Lag vs. Inside Diameter for 75-inch Test Line

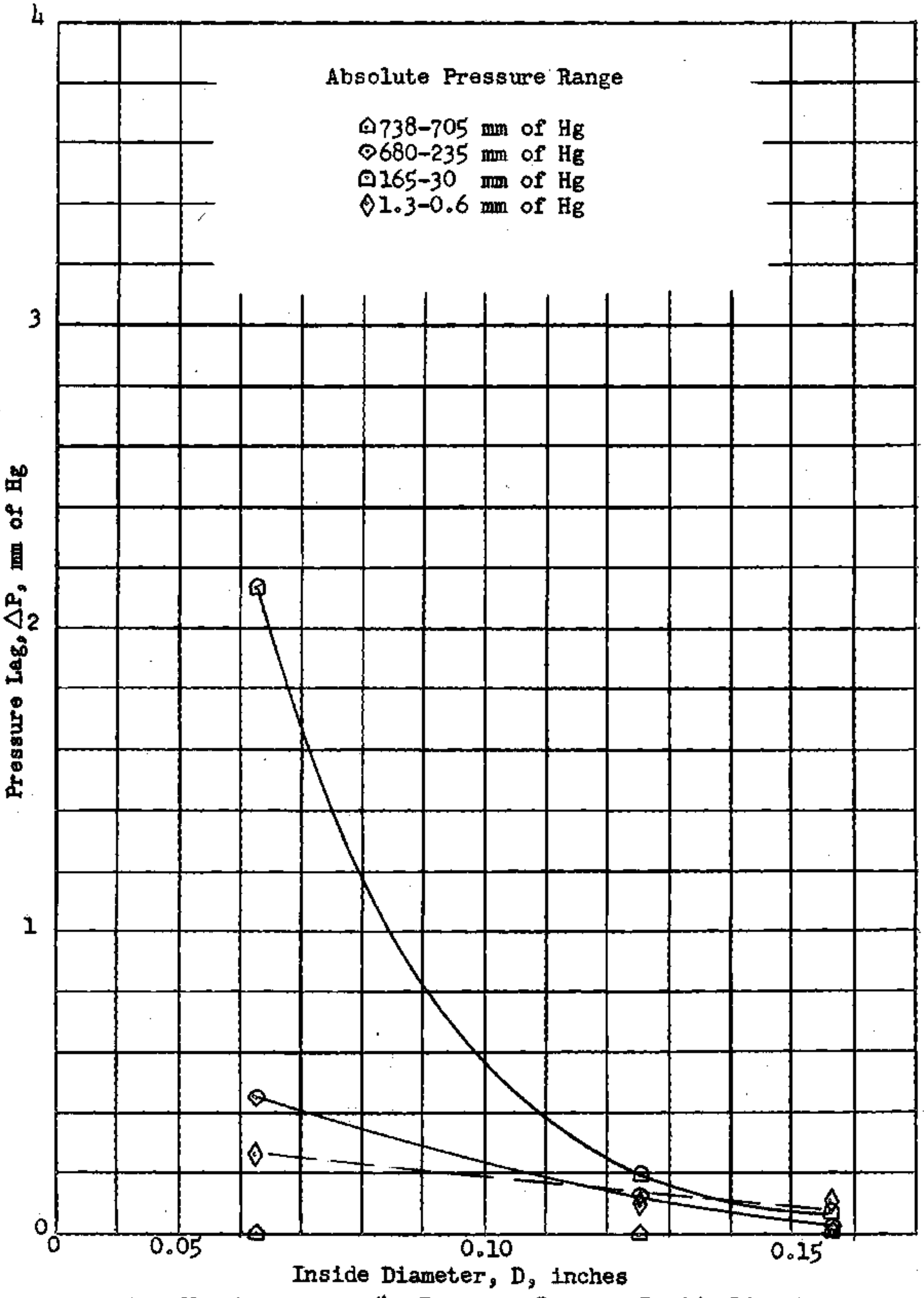


Fig. 29 Trajectory #4--Pressure Lag vs. Inside Diameter for 60-inch Test Line

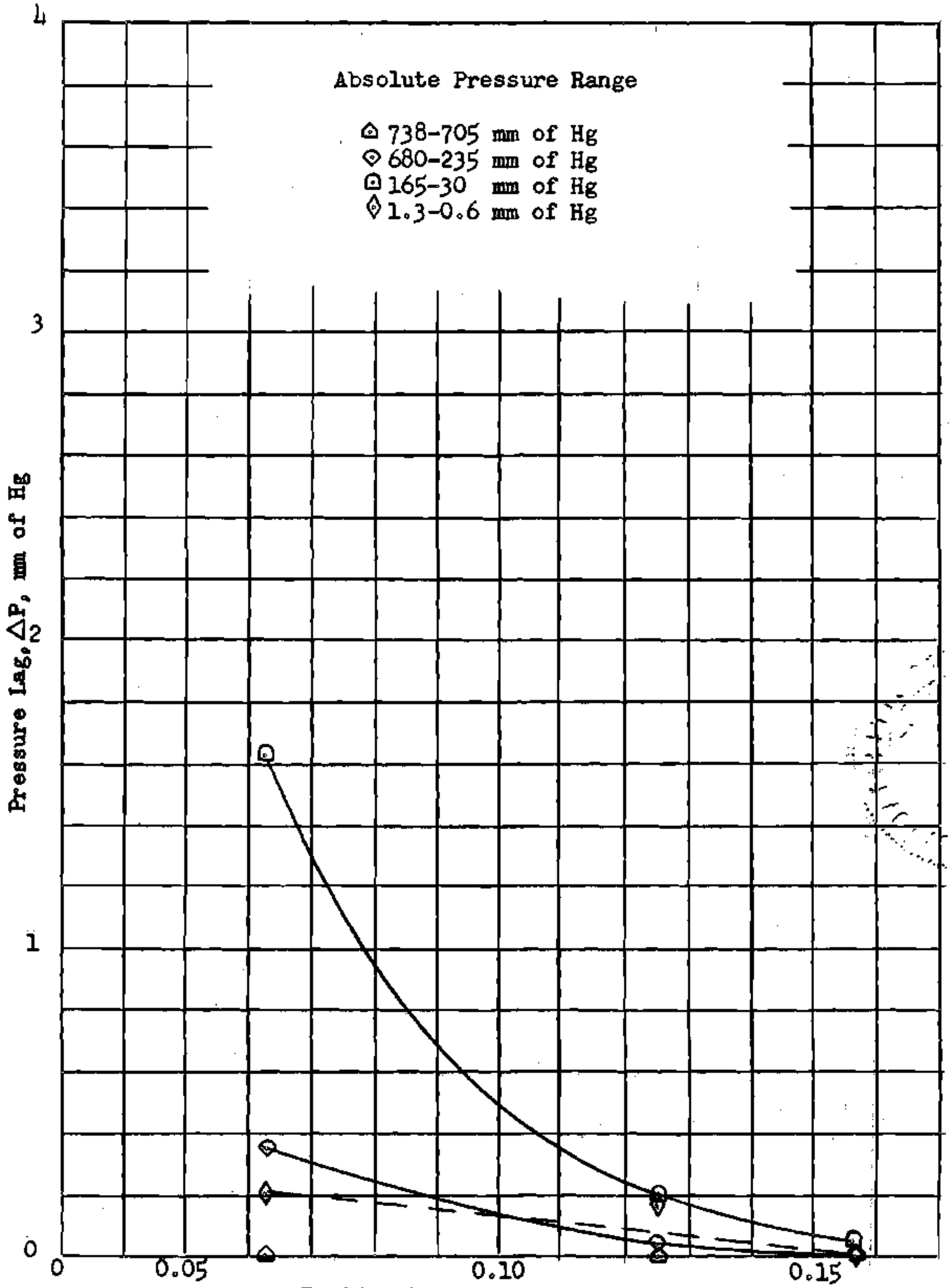


Fig. 30 Trajectory #4--Pressure Lag vs. Inside Diameter for 45-inch Test Line

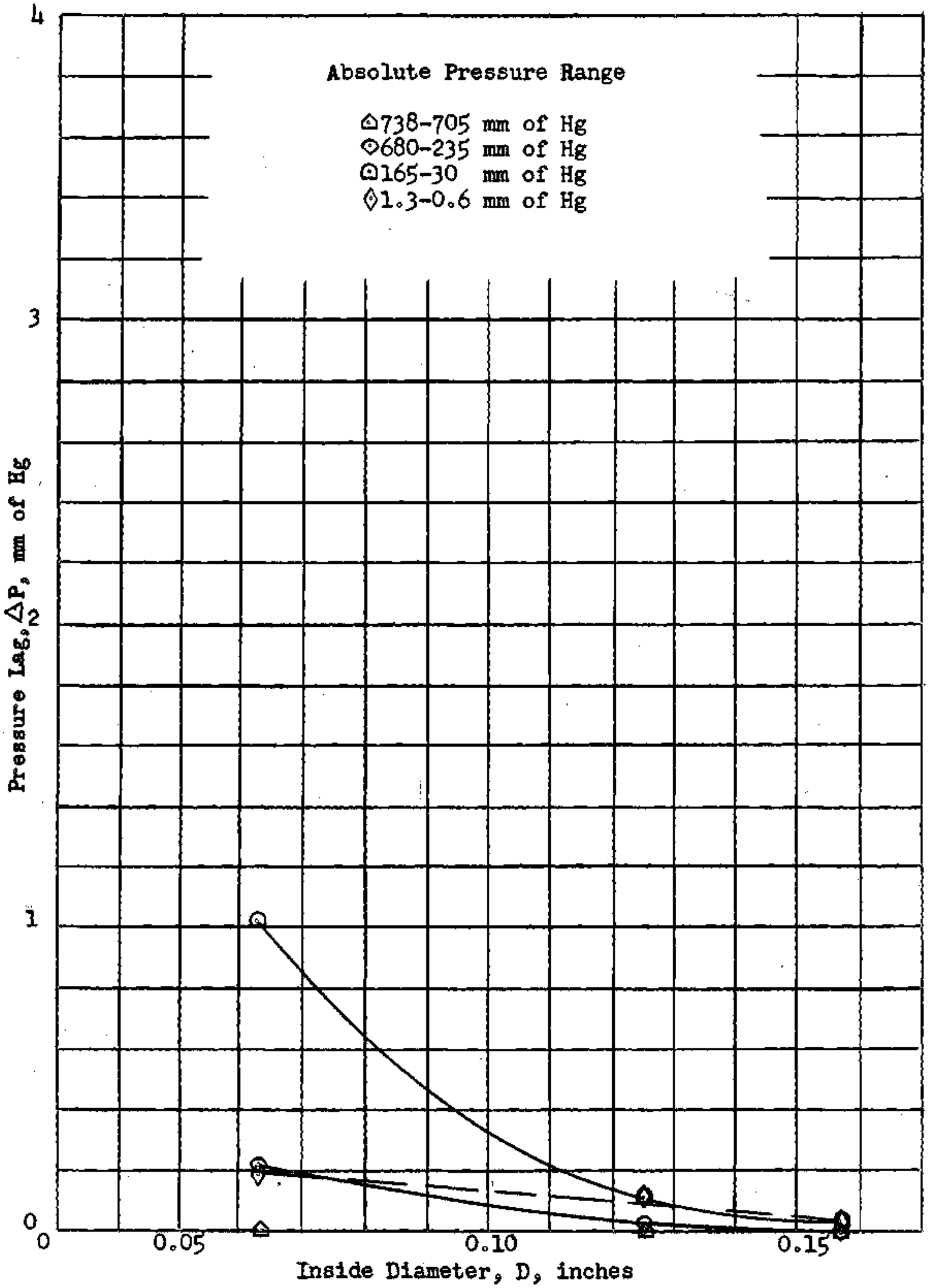


Fig. 31 Trajectory #4--Pressure Lag vs. Inside Diameter for 30-inch Test Line

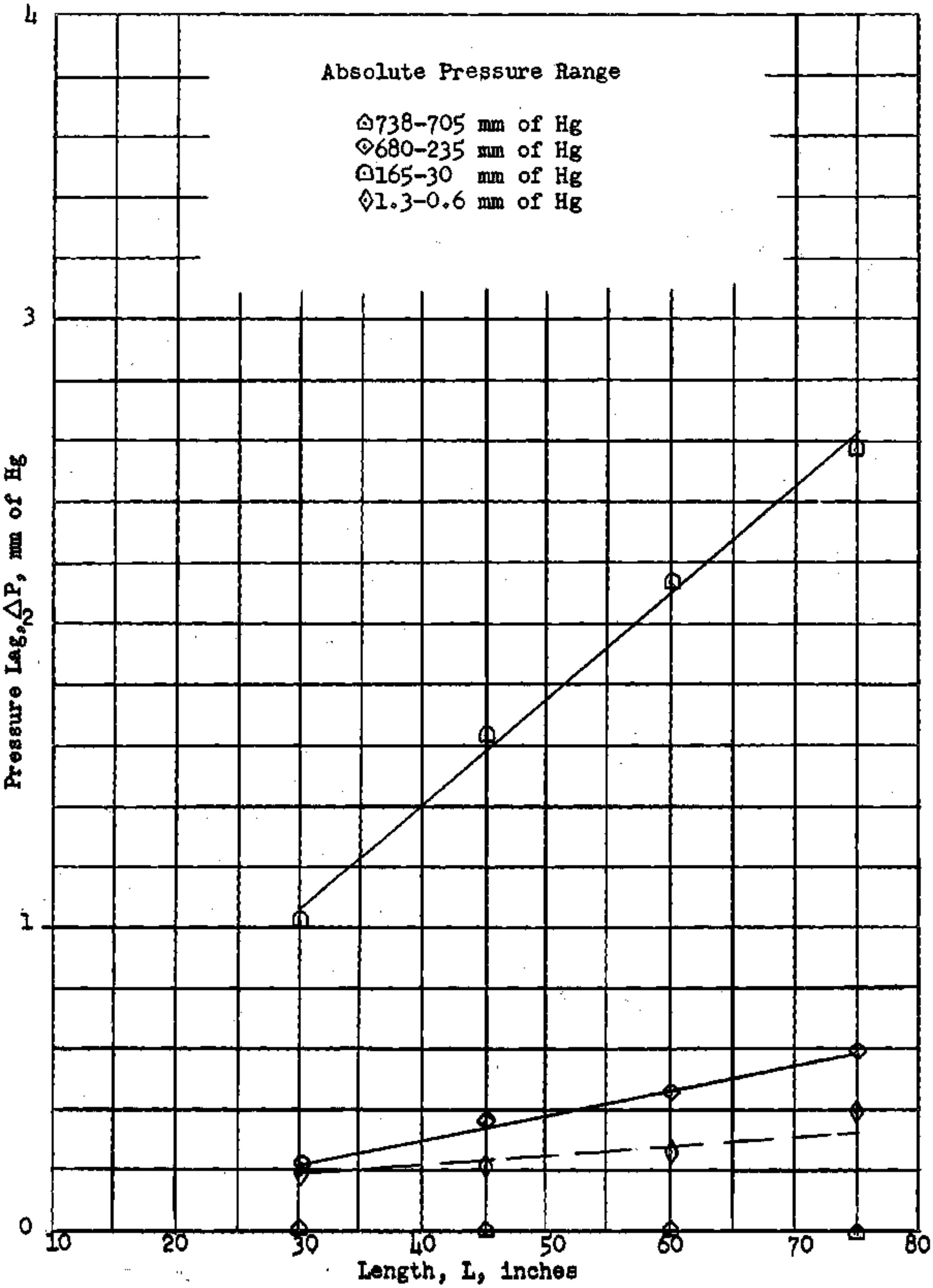


Fig. 32 Trajectory #4--Pressure Lag vs. Length for an Inside Diameter of 0.0625-inch Test Line

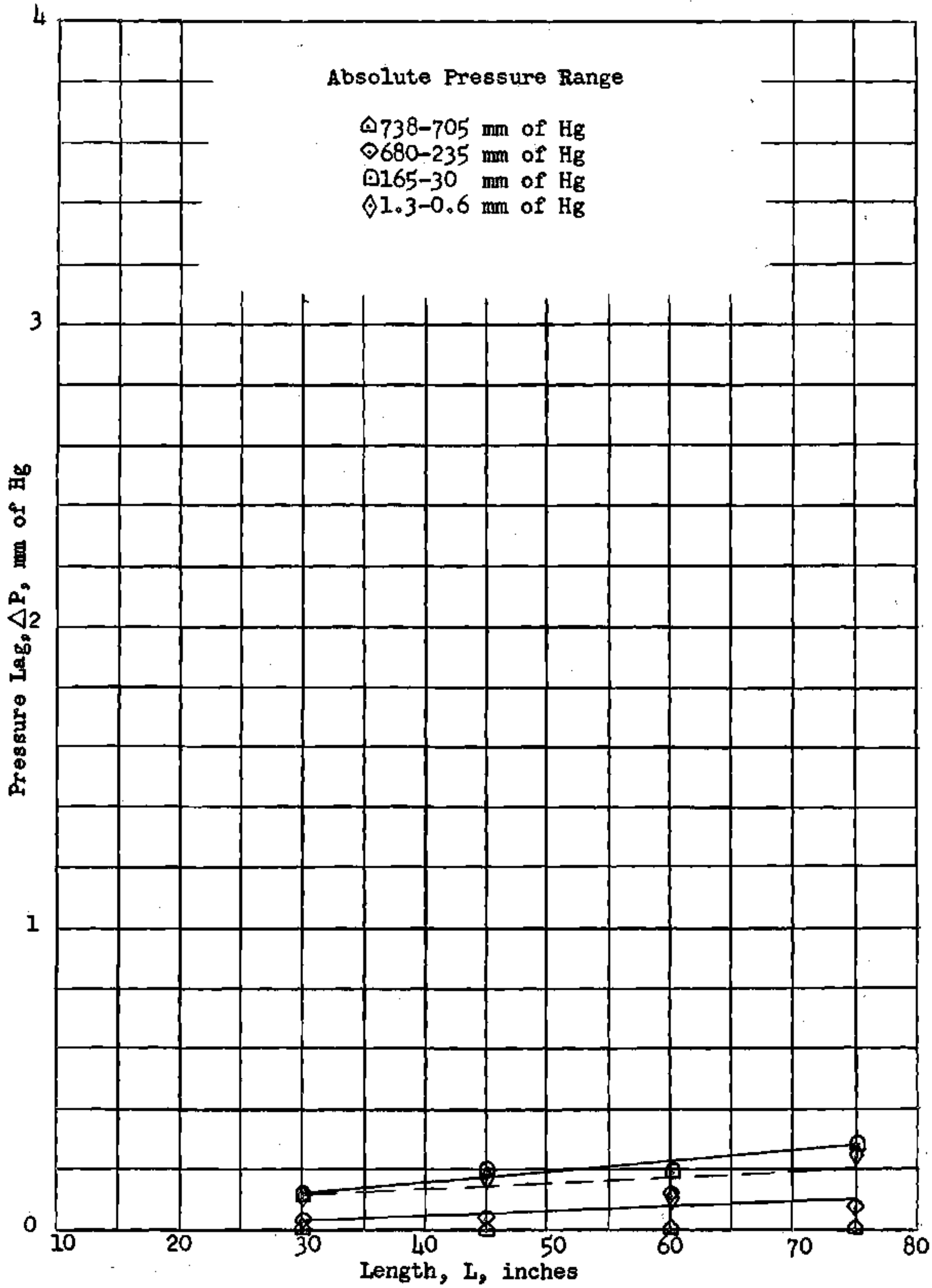


Fig. 33 Trajectory #4--Pressure Lag vs. Length for an Inside Diameter of 0.125-inch Test Line

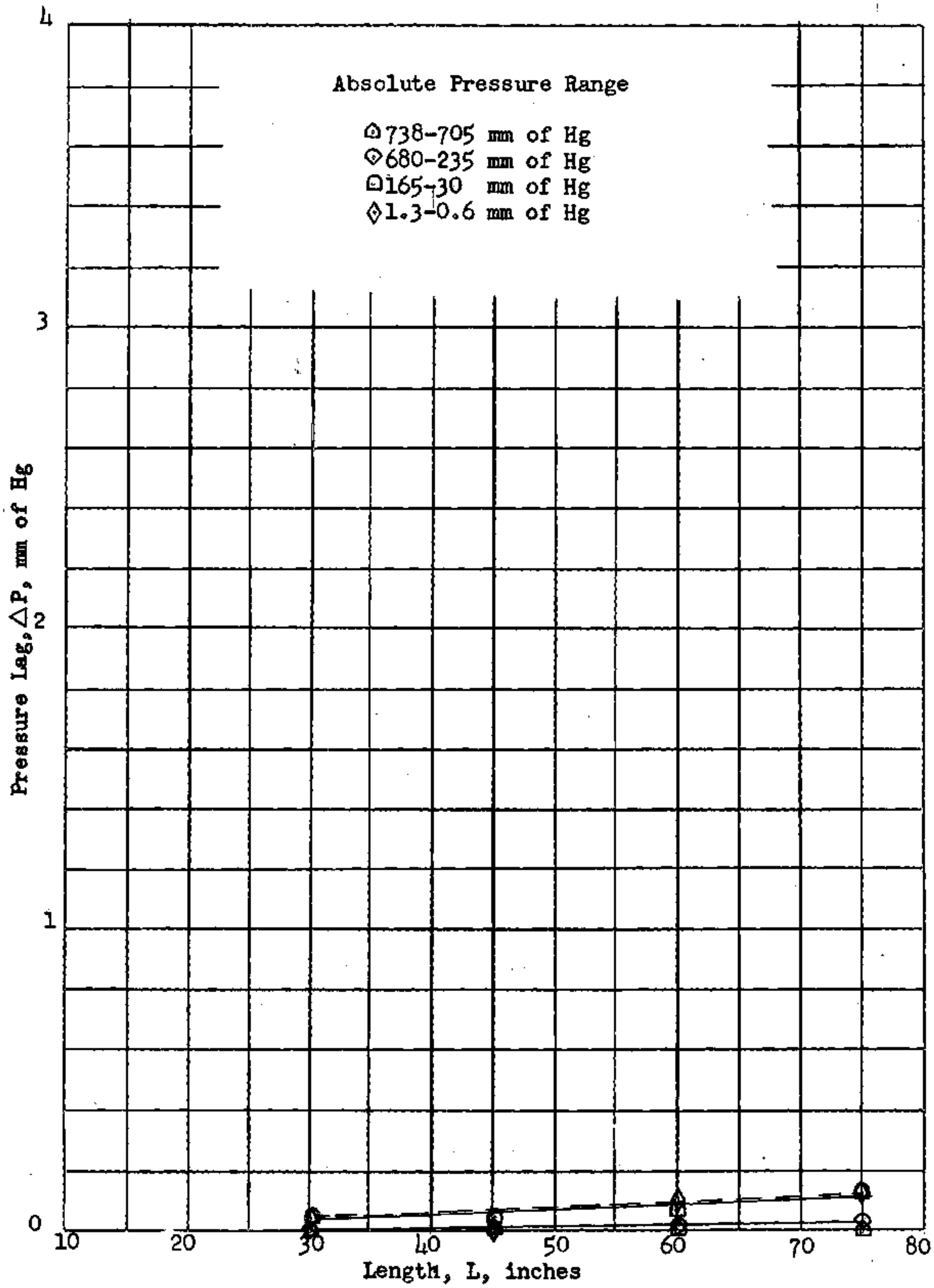


Fig. 34 Trajectory #4—Pressure Lag vs. Length for an Inside Diameter of 0.15625-inch Test Line

Accuracy.--Certain accuracies had to be established in the readout, reduction and final presentation of the test results. These accuracies are as follows:

1. Calibrations showed that the 0-15 psia pressure transducer was linear within 0.25 per cent of full scale. The recorder trace could be read accurately to ±1.0 mm of Hg, this accuracy was not sufficient at low pressures.

2. The 0-5 psia pressure transducer was used in the range of 0-20 mm of Hg absolute to offset 0-15 psia inaccuracy in this range. Calibrations showed that the 0-5 psia transducer was linear within 0.25 per cent of full scale. The recorder trace could be read accurately to ±0.03 mm of Hg.

3. The ±0.5 psi differential transducer was also linear within 0.25 per cent of full scale. The recorder trace could be read accurately to ±0.01 mm of Hg. However, it is doubtful that this accuracy remained constant due to temperature characteristics of the transducer causing some shift of the zero reference below approximately 5.0 mm of Hg absolute. Therefore an accuracy of ±0.1 mm of Hg was established.

CHAPTER V

CONCLUSIONS

From the experimental data obtained from this investigation, it can be concluded that:

1. There is no apparent simple relation between response pressure, initial pressure, end volume, line length, line inside diameter and trajectory. However, the equation,

$$\frac{dP_I}{dt} = K\left(P_R{}^2 - P_I{}^2\right)^{\frac{1}{2}}$$

where

K time constant, 1/seconds

P_I input pressure, mm of mercury

P_R response pressure, mm of mercury

t time, seconds

has been used by Vaughn (2) to predict pressure for ballistic plumbing systems. The feasibility for the use of the above relation is now being investigated by use of a digital computer at this writing.

2. Qualitatively, the pressure lag increases with increasing trajectory or rate of change of absolute pressure.

3. The largest effect on the magnitude of the pressure lag is produced by decreasing the line inside diameter below 0.125 inches.

4. For all trajectories presented in this investigation, a change

of line length has very little effect on the pressure lag for 0.125 and 0.15625 inches inside diameter test lines. However, a definite increase in the pressure lag occurs when the length is increased for a 0.0625 inches inside diameter test line.

5. The pressure lag varies approximately linearly with line length for constant line inside diameter and absolute pressure range.

CHAPTER VI

RECOMMENDATIONS

The following recommendations are made:

1. Further studies of the same nature as the investigation presented in this report should be made with a more accurace relay circuit in order to establish a better relation for the effect of different trajectories on pressure lag.

2. Similar investigations should be made to include the effects of end volume and line fittings.

REFERENCES

1. Cremin, J. W., An Experimental Study for the Prediction of Pressure Lag Inherent in Ballistic Missile Plumbing Systems--Part I, Unpublished Master's Thesis, Georgia Institute of Technology, 1958.

2. Vaughn, H., "The Response Characteristics of Airplane and Missile Pressure Measuring Systems," Aeronautical Engineering Review, Vol. 11, November, 1955, pp. 664-669.